U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-257 128

West Electrostatic Precipitator System Study

Southern Research Inst.

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, N C

May 76

257105

PB 257 128

EPA-600/2-76-142
May 1976

Environmental Protection Technology Series

[illegible]

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

PB257128

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-76-142
2.
3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Wet Electrostatic Precipitator System Study
5. REPORT DATE May 1976
6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John P. Gooch and Alan H. Dean
8. PERFORMING ORGANIZATION REPORT NO. SORI-EAS-75-651 3133
9. PERFORMING ORGANIZATION NAME AND ADDRESS

Southern Research Institute
2000 Ninth Avenue South
Birmingham, Alabama 35205

10. PROGRAM ELEMENT NO. 1AB013; ROAP 21ACX-095
11. CONTRACT/GRANT NO. 68-02-1313
12. SPONSORING AGENCY NAME AND ADDRESS

EPA, Office of Research and Development
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED Final; 5/73-4/75
14. SPONSORING AGENCY CODE EPA-ORD
15. SUPPLEMENTARY NOTES IERL-RTP Project Officer for this report is L.E. Sparks, Mail Drop 61, Ext 2925.

16. ABSTRACT

The report describes a study of wet electrostatic precipitators (WESP's) through laboratory experiments, a field test of a full-scale unit, interviews with manufacturers and users, and a literature survey. Experiments were aimed at determining collection efficiency as a function of particle size at varying current densities and specific collection areas. The results agreed reasonably with those predicted by simulating the experimental conditions with a mathematical model. The feasibility of collecting SO2 and particulate in a WESP was examined. As expected, calculation of ion transport rates indicates that only an insignificant amount of SO2 can be removed by selective ionization of SO2 molecules. Mass transfer calculations indicated that irrigated electrode surfaces would not provide sufficient interfacial area for desired SO2 removal levels. Based on conventional geometry and stainless steel construction, a WESP/scrubber device would be more costly than a scrubber-only system because of high WESP capital costs. The effectiveness of a WESP as a mist eliminator following a scrubber was calculated to be a function of the particle size distribution and the concentration of the mist to be collected. The field test and literature survey showed that WESP's have been used effectively to control fine particle emissions in the aluminum, iron and steel, chemical and petrochemical fields.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Electrostatic Precipitators Dust Sulfur Dioxide Aluminum Industry Iron and Steel Industry Chemical Industry Petrochemistry	Air Pollution Control Stationary Sources Wet Electrostatic Precipitators Collection Efficiency Particulates	13B 07A 11G 08G 07B 11F

18. DISTRIBUTION STATEMENT Unlimited
19. SECURITY CLASS (This Report) Unclassified
20. SECURITY CLASS (This page) Unclassified
21. NO. OF PAGES 206
22. PRICE 7.75

EPA Form 2220-1 (9-73)

PRICES SUBJECT TO CHANGE

EPA-600/2-76-142
May 1976

WET ELECTROSTATIC PRECIPITATOR SYSTEM STUDY

by

John P. Gooch and Alan H. Dean

Southern Research Institute
2000 Ninth Avenue South
Birmingham, Alabama 35205

Contract No. 68-02-1313
ROAP No. 21ACX-095
Program Element No. 1AB013

EPA Project Officer: Leslie E. Sparks

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

1-a

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

i-b

ABSTRACT

This report describes a study of wet electrostatic precipitators (WESP) through laboratory experiments, a field test of a full-scale unit, interviews with manufacturers and users, and a literature survey. Experiments were conducted with the objective of determining collection efficiency as a function of particle size at varying current densities and specific collection areas. The results obtained were in reasonable agreement with those predicted by simulating the experimental conditions with a mathematical model. The feasibility of collecting SO_2 and particulate in a WESP was examined. As would be expected, calculation of ion transport rates indicate that only an insignificant amount of SO_2 can be removed by selective ionization of SO_2 molecules. Mass transfer calculations indicated that irrigated electrode surfaces would not provide sufficient interfacial area for desired SO_2 removal levels. Based on conventional geometry and stainless steel construction, a WESP-scrubber device would be more costly than a scrubber-only system because of high WESP capital costs. The effectiveness of a WESP as a mist eliminator following a scrubber was shown by calculation to be a function of the particle size distribution and the concentration of the mist to be collected. The field test and literature survey indicated that WESPs have been used effectively to control fine particle emissions in the aluminum, iron and steel, chemical, and petrochemical industries.

TABLE OF CONTENTS

Page

Abstract ii

List of Figures iv

List of Tables ix

Sections

I Summary and Conclusions 1

II Introduction 3

III Laboratory Studies 4

IV Evaluation of Full-Scale Wet Electrostatic Precipitator Installations 28

V Analysis of Potential Wet ESP Applications 53

VI Recommended Research and Development 69

VII Literature Study 72

VIII Summary of Status of WESP Technology and Design Methods 168

IX Acknowledgments 170

X References 171

XI Appendix A 176

XII Appendix B 177

FIGURES

No.		Page
1	Plan and side views	5
2	Wet wall precipitator section at corona wire	7
3	Completed wet ESP test assembly	8
4	Gas burner assembly	9
5	Voltage-current relationship for section 2 of pilot scale wet ESP	11
6	Inlet particle size distributions from Brink data	14
7	Experimentally measured and ideally calculated fractional collection efficiencies in the laboratory precipitator	15
8	Experimentally measured, ideally calculated, and sneakage-corrected fractional collection efficiencies for a current density of 53.8 nA/cm^2 and a gas velocity of 0.72 m/sec in the laboratory precipitator	16
9	Experimentally measured, ideally calculated, and sneakage-corrected fractional collection efficiencies for a current density of 26.9 nA/cm^2 and a gas velocity of 0.72 m/sec in the laboratory precipitator	17
10	Experimentally measured, ideally calculated, and sneakage-corrected migration velocities as a function of particle size in the laboratory precipitator	19
11	Experimentally measured, ideally calculated, and sneakage-corrected migration velocities as a function of particle size for a current density of 53.8 nA/cm^2 and a gas velocity of 0.72 m/sec in the laboratory precipitator	20
12	Experimentally measured, ideally calculated, and sneakage-corrected migration velocities as a function of particle size for a current density of 26.9 nA/cm^2 and a gas velocity of 0.72 m/sec in the laboratory precipitator	22

FIGURES
(Continued)

13 Effective migration velocities from Climet and Brink efficiency determination with DOP particulate at 50 nA/cm^2 23

14 Effective migration velocities for SO_2-DOP particulate experiment (gas velocity = 0.76m/sec) 27

15 Schematic of scrubber-precipitator system and sampling locations 29

16 Schematic of primary emission control system 30

17 Optical and diffusional sizing system 31

18 Andersen data on log probability co-ordinates 33

19 Cumulative size distributions on a number basis for various industrial particulate sources as measured by optical and diffusional methods 34

20 Measured fractional efficiencies for a wet electrostatic precipitator with the operating parameters as indicated, installed downstream of a spray type scrubber on an aluminum reduction pot line 35

21 Voltage current relationship (manual control) and operating ranges (automatic control) 38

22 Discharge electrodes for wet ESP units at British Steel 44

23 Lurgi discharge electrodes 48

24 Schematic diagram of scrubber-wet precipitator system 54

25 Computer model projections for $50x10^{-9}$ amps/cm^2 and 50 KV 58

26 Computer model projections for $33x10^{-9}$ amps/cm^2 and 47.3 KV 59

27 Computer model projections for droplet size distribution, $33x10^{-9}$ amps/cm^2, 47.3 KV 66

28 Theoretical collection efficiencies as a function of particle diameter 68

FIGURES
(Continued)

29 A flow chart showing the steps in the steelmaking process from the basic raw material and scrap input to the finished product 73

30 Effect of burden improvement on dust rate from a blast furnace to its dust collecting system 76

31 Typical wet type pipe precipitator cleaning blast furnace gases 83

32 Flow diagram for wet cleaning iron blast furnace gas with electrostatic precipitator 84

33 Blast furnace statistics for period 1920-1969 85

34 Distribution of precipitator inlet gas temperature Blast furnace installations 86

35 Distribution of precipitator inlet dust loading Blast furnace installations 87

36 Distribution of precipitator gas velocity Blast furnace installations 88

37 Distribution of precipitator field strength Blast furnace installations 89

38 Distribution of precipitator input power Blast furnace installations 90

39 Design efficiency trends over the period 1939-1969 prorated on acfm basis for blast furnace installations 91

40 Relationship between collection efficiency and specific collection area for electrostatic precipitators operating on blast furnace installations 92

41 Comparison of actual performance to design performance on blast furnaces (Basis:ratio of migration velocities calculations using Deutsch equation) 93

42 Dust output survey as a function of coke rate and melt rate 106

43 Particle size studies made with dusts from hot and cold blast cupolas 107

FIGURES
(Continued)

44 Hot-blast cupola plant (melting rate: 6 m. ton/hr) with wet electrostatic precipitator for cleaning the waste gases 108

45 Waste and top gas cleaning with wet electrostatic precipitator and venturi in series 110

46 Coke oven flow diagram 113

47 Typical pipe type electrostatic precipitator for collection of tar 116

48 An integral tar collecting pipe type precipitator 117

49 Concentric ring detarrer 118

50 A process flow diagram of production of carburetted water gas 122

51 Oil shale retorting process 123

52 A single-stage vertical wire and pipe unit 124

53 Plate-type precipitator used for detarring 125

54 Typical flow chart for sulfur-burning contact plant 130

55 Basic flow diagram of contact-process sulfuric acid plant burning spent acid 132

56 Particle size distribution of sulfuric acid mist from commercial contact plants 134

57 Wire-in-tube acid mist precipitator 135

58 Installed cost of sulfuric acid mist precipitators, 1965-1969 143

59 Flow diagram for typical thermal-process phosphoric acid plant 146

60 Electrostatic precipitator used for P_2O_5 mist removal 148

61 Diagram of the Bayer Process 151

FIGURES
(Continued)

62 Prebake Reduction Cell schematic arrangement 152

63 Vertical Stud Soderberg Cell schematic arrangement 153

64 Horizontal Stud Soderberg Cell schematic arrangement 154

65 Particle size weight distribution, pot line primary effluent 156

66 Composite particle size distribution by weight for aluminum reduction cell air emissions (Kaiser Aluminum and Chemical Corporation Plant at Tacoma, Washington pot line 4) at the exit of the reduction cell 157

67 Anodic gas purification plant flow sheet 159

68 Cost data for wet precipitators 164

TABLES

No.		Page
1	Typical inlet and outlet particle size data for wet ESP experiments	13
2	SO_2 removal experiments	25
3	Applied voltage in wet ESP test unit at 50 $\mu A/ft^2$ current density	26
4	Mass train test results - 553 wet ESP	36
5	Precipitation rate parameters	41
6	Performance characteristics of wet precipitators specified by British Steel	43
7	Mikropul wet electrostatic precipitator installations	50
8	Test results obtained by Research Cottrell on a blast furnace wet precipitator installation	52
9	Power requirement comparison for particulate controls in SOx removal systems	60
10	Capital cost estimates for particulate control in particulate-SOx removal system	62
11	Operating cost estimates for particulate control in particulate-SOx removal system $/yr	63
12	Size distribution of droplets at a spray scrubber exit	65
13	Chemical analysis of blast furnace flue dusts	78
14	Weight percent composition of dust samples from blast furnace gas cleaning plant	79
15	Size analysis of blast furnace flue dust	80
16	Electric arc steel furnace fume emission data	95
17	Electric furnace dust composition	96
18	Electric steel furnace fume particle size data	98
19	Fume cleaning for steelmaking processes 1969 (B SC)	99

TABLES
(Continued)

20 Chemical composition of cupola dust 104

21 Dust content of cupola waste gases 105

22 Cost comparison for various dust collectors for cleaning waste gases of a hot blast cupola 111

23 Typical coke oven gas precipitator design parameters 115

24 Average design parameters for coke oven precipitators 119

25 Precipitator economics for detarring of coke oven gas (time period 1959-1969) 119

26 A summary of design data of electrostatic precipitators on various applications for removing tar and oil mist over period 1940 to 1963 128

27 Precipitator inlet mist loading Summary of performance statistics sulfuric acid mist precipitator (1945-1969) 137

28 Precipitator inlet gas temperature Summary of performance statistics sulfuric acid mist precipitator (1945-1969) 138

29 Precipitator input power Summary of performance statistics sulfuric acid mist precipitator (1945-1969) 139

30 Precipitator field strength Summary of performance statistics sulfuric acid mist precipitator 140

31 Precipitator gas velocity Summary of performance statistics sulfuric acid mist precipitator 141

32 Summary of sulfuric acid mist precipitator costs 1960-1969 142

33 Distribution of ratio (R) for sulfuric acid mist precipitators (1945-1969) 144

TABLES
(Continued)

34	Plant capacity for manufacturing primary aluminum	149
35	Typical performance data of wet precipitator at the Dalles	160
36	Control equipment considered for the primary aluminum industry	161
37	Results of EPA source tests fluoride and particulate primary aluminum industry	162
38	Legend for tables and figures	163
39	Typical electrical conditions for wet precipitator at the Dalles	165
40	Emission measurements on electrostatic precipitator No. 1, Martin Marietta Plant at Goldendale, Washington	166
41	Summary of measured emissions	167

SECTION I
SUMMARY AND CONCLUSIONS

A flexible laboratory scale electrostatic precipitator was designed and constructed to (1) obtain performance data on fine particle collection under idealized conditions and (2) to evaluate the feasibility of incorporating a wet precipitator scrubber-device in a gas cleaning system for coal-fired boilers. Experiments were conducted with the objective of determining collection efficiency as a function of particle size at varying current densities and specific collection areas using dioctylphthalate aerosol. The results obtained were in reasonable agreement with those predicted by simulating the experimental conditions with a mathematical model of electrostatic precipitation.

Calculations were performed to determine the maximum amount of SO_2 which could be transported to the collection electrode by selective ionization of SO_2 molecules. As would be expected, the results indicated that an insignificant fraction of the SO_2 can be removed by this mechanism. Mass transfer calculations were also performed to estimate the SO_2 which could be absorbed by a basic solution irrigating the collection electrodes. It was found that the interfacial area provided by the collecting electrodes was insufficient to obtain significant SO_2 removal levels. Experiments conducted in the laboratory test unit with NaOH solution irrigating the collecting electrodes indicated that no significant increase in SO_2 removal rates occurred as a result of energizing the precipitator power supplies. Simultaneous collection of SO_2 and DOP aerosol in the laboratory test unit indicated a decrease in SO_2 removal, presumably caused by a decrease in electrode wettability.

Cost estimates were made for a full-scale wet ESP-scrubber device for collection of SO_2 and particulate in a power plant flue gas cleaning system. The estimates indicated that, although the WESP system would use less energy, a scrubber-only system is more economical to operate because of the high capital costs (using stainless steel construction and conventional electrode geometries) of a WESP. Electrode scaling with the WESP is a potentially serious problem which would require pilot plant trials for an adequate evaluation.

The effectiveness of a wet electrostatic precipitator as a mist eliminator following a scrubber was shown by calculation to be a function of the particle size distribution and the concentration of the mist to be collected. High droplet concentrations, such as those existing at the outlet of a spray scrubber, may limit the performance of a WESP through space charge suppression of the corona current.

A field test of a full scale wet electrostatic precipitator was conducted, and an analysis of the results indicated that the collection efficiency as a function of particle size relationship is in fair agreement with the predictions of the mathematical model over the particle diameter range 0.2 μm to 1.3 μm. For larger particles, the measured collection efficiencies were significantly lower than the theoretical predictions, possibly because of liquor carryover from the electrode irrigation system. The WESP was collecting fume from an aluminum pot line. Overall mass collection efficiencies on the fume, in which about 65% of the mass consisted of sub-micron particles, ranged from 95.0 to 98.0% at a specific collecting area of about 62 $m^2/(m^3/sec)$. Corrosion and deposit formation in the liquor supply system have occurred at this installation.

An evaluation of current WESP technology was conducted by a literature survey and by contacts with manufacturers and users. Both plate and pipe collecting electrodes have been effectively utilized in collecting fumes and mists from metallurgical and chemical processes. The largest recent application of WESP has been in the collection of fume from aluminum pot lines. Duct-type collecting electrodes are generally used for the application in which relatively large gas volume flows are to be cleaned. The advantages of plate electrodes as opposed to pipe electrodes are less expensive construction and the flexibility of allowing variations in electrical sectionalization. Pipe electrodes can be more uniformly irrigated than plates, and gas by-passage (sneakage) is not a factor. Wire-pipe WESP's usually consist of only one electrical section in the direction of gas flow.

SECTION II
INTRODUCTION

This report describes a study of wet electrostatic precipitator technology which was conducted with the following objectives: (1) develop methods for calculating performance of WESP's, (2) evaluate the potential of a wet electrostatic precipitator as a device for collecting particulate and sulfur oxides, or mists exiting a scrubber, in a gas cleaning system for a utility power station, and (3) evaluate the status of wet precipitator technology. Wet electrostatic precipitators, for the purposes of this study, are defined as conventional electrostatic precipitator geometries, consisting of either wire-pipe or wire duct design, in which either a liquid or solid phase particulate is collected with electrode irrigation, or in which a liquid phase aerosol is collected without electrode irrigation.

An electrostatic precipitator collecting a liquid aerosol under laboratory conditions offers an opportunity to study performance in the absence of unmodelled processes such as particle reentrainment and back corona. Therefore, a laboratory-scale wet ESP can be used to evaluate mathematical procedures for modelling particle collection. The following sections describe experiments performed with a laboratory-scale WESP, and compare the experimental results with those obtained from a mathematical model developed under other EPA contracts. The model is then used to evaluate potential WESP applications in utility power plant gas cleaning systems.

The status of existing wet ESP technology was evaluated by conducting a performance test on a recently installed WESP in the aluminum industry, and by conducting a literature survey. Information was also obtained from WESP manufactures and users.

SECTION III
LABORATORY STUDIES

DESIGN OF BENCH-SCALE TEST UNIT

A flexible test unit capable of treating about 0.0737 m^3/sec of synthetic flue gas (156 ft^3/min)* was designed with the following objectives in mind.

> To obtain fundamental performance data for particulate collection, especially in the diameter range of 2.0 μm and smaller.
>
> To evaluate the feasibility of incorporating a wet precipitator scrubber device in a gas cleaning system for coal-fired boilers.

The general arrangement of the test facility and a side view with dimensions are given in Figure 1. Plate-to-plate spacing is 12.7 cm (5 in.) and the collecting electrode area is 2.32 m^2 (25 ft^2). A gas velocity of 1.52 m/sec (5 ft/sec) gives a flow rate of 0.0737 m^3/sec which results in a Reynolds number of about 16000 (well within the turbulent flow region) and an A/V ratio of 31.5 m^2/ (m^3/sec) (160 ft^2/1000 cfm). The test unit can also be assembled with plate-to-plate spacings of 18.75 cm and 25.4 cm.

The test unit has sufficient space available to accommodate an assembly consisting of alternating scrubbing and collecting sections, with the spray sections comprising one-half the length of the collecting sections. Under this contract, the spray sections were not utilized. Figure 2 is a detailed cross-section of the unit at a corona wire in a precipitation section. The numbers in circles are call-out numbers which refer to details in detail drawings that are not shown.

The high-voltage insulators for the test unit are designed to isolate the discharge electrodes in the presence of a wet environment. This was a difficult design problem for a test unit designed to obtain fundamental performance data, since bleed air to dry the insulators and large open spaces around the insulators are very undesirable from the standpoint of interpreting experimental data. Originally, the plan was to isolate Teflon feed-through insulators at the top of the assembly in a plexiglas conduit purged with heated air. However, water drops from the spray nozzles could deposit on the plexiglas, and the conduit

---

*Environmental Protection Agency policy is to express all measurements in agency documents in metric units. When implementing this practice will result in undue costs or lack of clarity, conversion factors are provided for the non-metric units used in the report. Conversion factors are given in Appendix A.

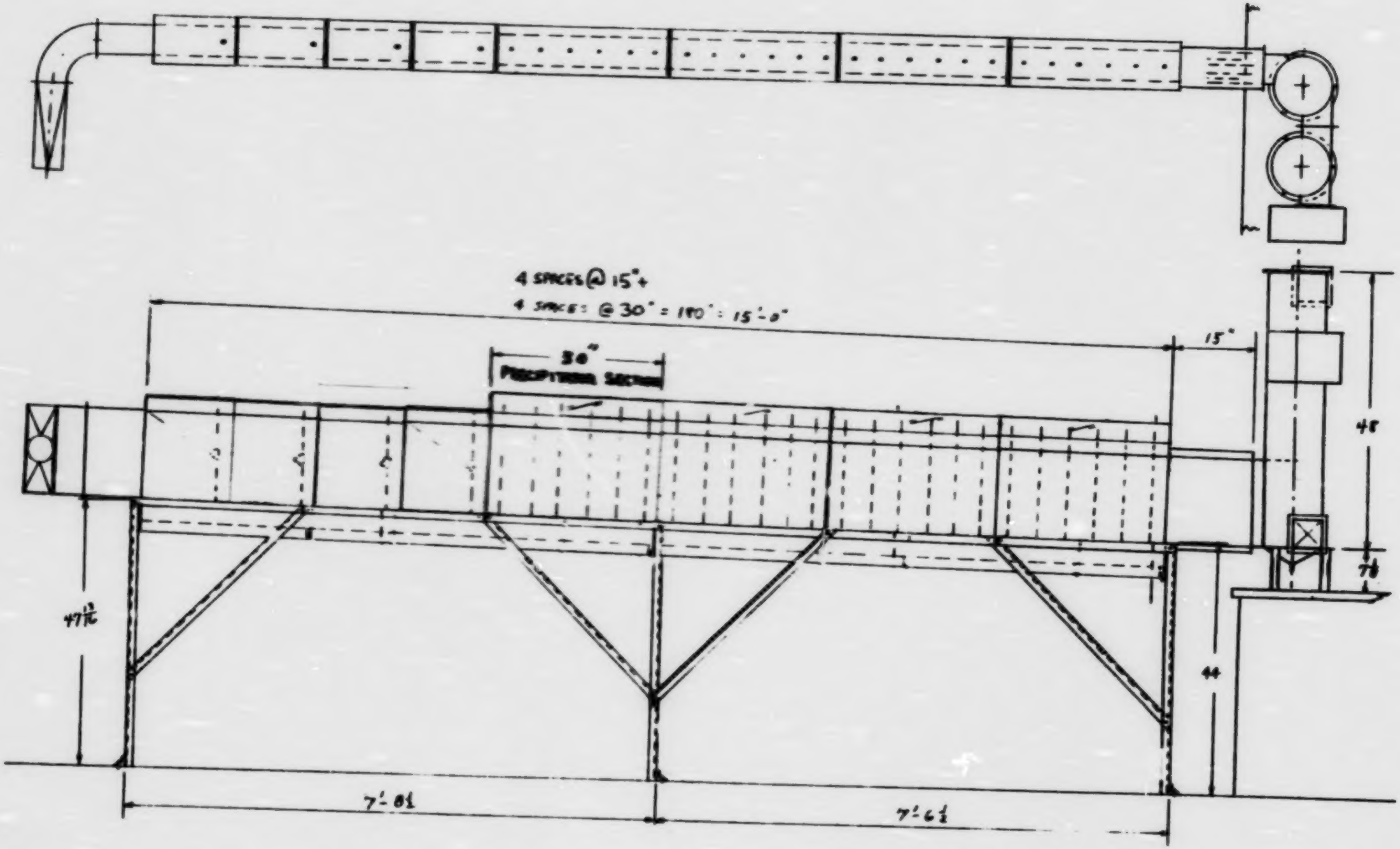

4 SPACES @ 15"+
4 SPACES @ 30" = 180" = 15'-0"
30"
PRECIPITATOR SECTION
15"
48
7 3/8
44
47 13/16
7'-8 1/2
7'-6 1/2

Figure 1. Plan and Side Views of Pilot ESP Test Facility

could not be maintained at a temperature level sufficient to insure quick evaporation. As a result of the above potential hazard, an alternative concept of using a heated epoxy insulator was designed. The epoxy is a formulation which has a high thermal conductivity and a low electrical conductivity. The heater embedded in the epoxy was designed to maintain the temperature of the insulator at about 250°F. Figure 2 shows a cross-section of the cast epoxy insulator, which is used to jacket the Teflon feed-through insulator surrounding the corona wire. This design was only partially successful because of problems with air bubbles in the casting and cracks forming in the epoxy during operation of the internal heaters. The test unit can at present be operated for short periods of time with electrode irrigation with this design, but long-term operation is not possible due to spray droplet accumulation on the insulator surfaces. A solution to the problem would require a design that would enable higher insulator surface temperature to be maintained.

Although Figure 2 shows the plates irrigated by sprays and weirs, only the sprays were used due to non-uniform flow along the length of the weirs. Experiments with the collecting electrode spray assembly indicated the expected difficulty in maintaining uniform sheet flow on the electrode surfaces. Polishing the plate surface with emery cloth was found to be beneficial, but repolishing was necessary immediately prior to spraying the plates with water, apparently because of a change in the wettability of the surfaces upon exposure to the atmosphere. In an attempt to eliminate the time variation of the wettability, a sample plate was sandblasted with medium grit sand. This procedure resulted in much improved plate wetting, and the wettability did not decrease upon exposure to the atmosphere. All plates were therefore sandblasted prior to their installation in the test unit.

Photographs of the completed installation are shown in Figures 3 and 4. Three electrical sections are employed, the first two of which each consists of 0.581 m^2 (6.25 ft^2); the third power supply feeds 1.162 m^2 (12.50 ft^2). Figure 4 shows a side view of the test unit, including the heater assembly, spray towers, a mixing chamber for studying condensation growth (constructed as part of another project), the water piping and drainage system, the power supplies, inlet sampling ports, and the electrified sections. Figure 4 shows a front close-up view of the gas-fired burner assembly, including a hopper for feeding solid particulate, and a steam venturi-ejector device which can be used for redistribution of particulate. The burner assembly has been equipped with a commercial hot water controller with proportional band control on a pressure reducer in the gas supply line. The pressure is controlled by a temperature bulb in the warm water outlet of the scrubber. The controller also has a thermostatically controlled pilot and main gas valve to shut down in case of flame failure.

Voltage-current curves were obtained with and without water

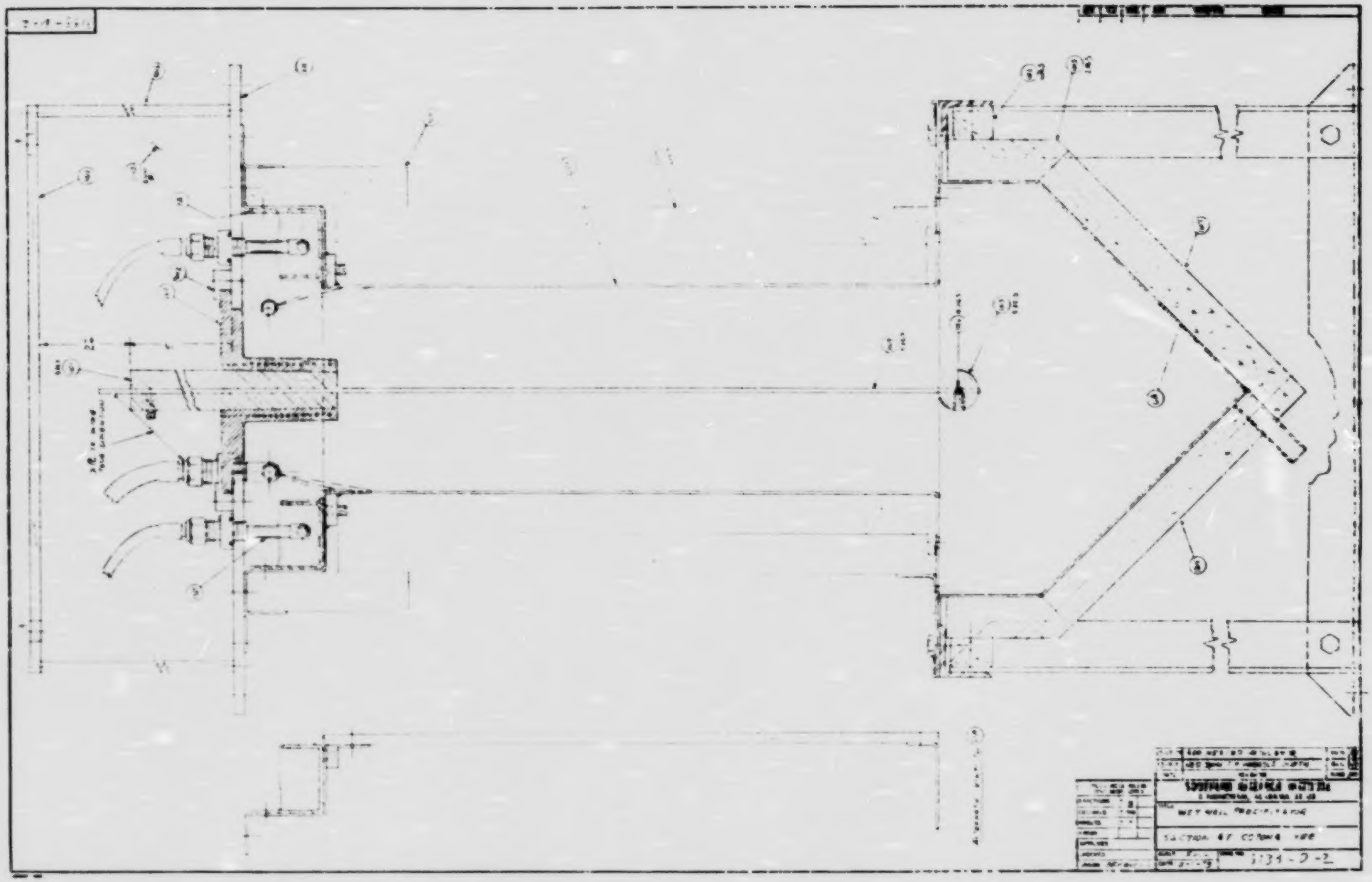

WET WALL PRECIPITATOR
SECTION AT CORONA WIRE

Figure 2. Wet Wall Precipitator Section at Corona Wire

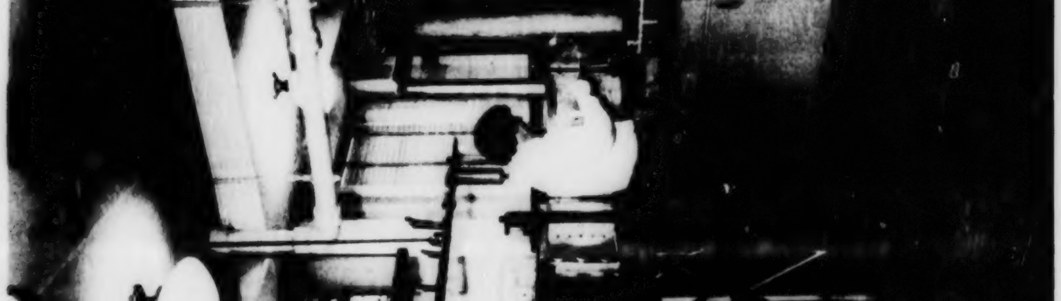


Figure 3. Completed wet ESP test assembly

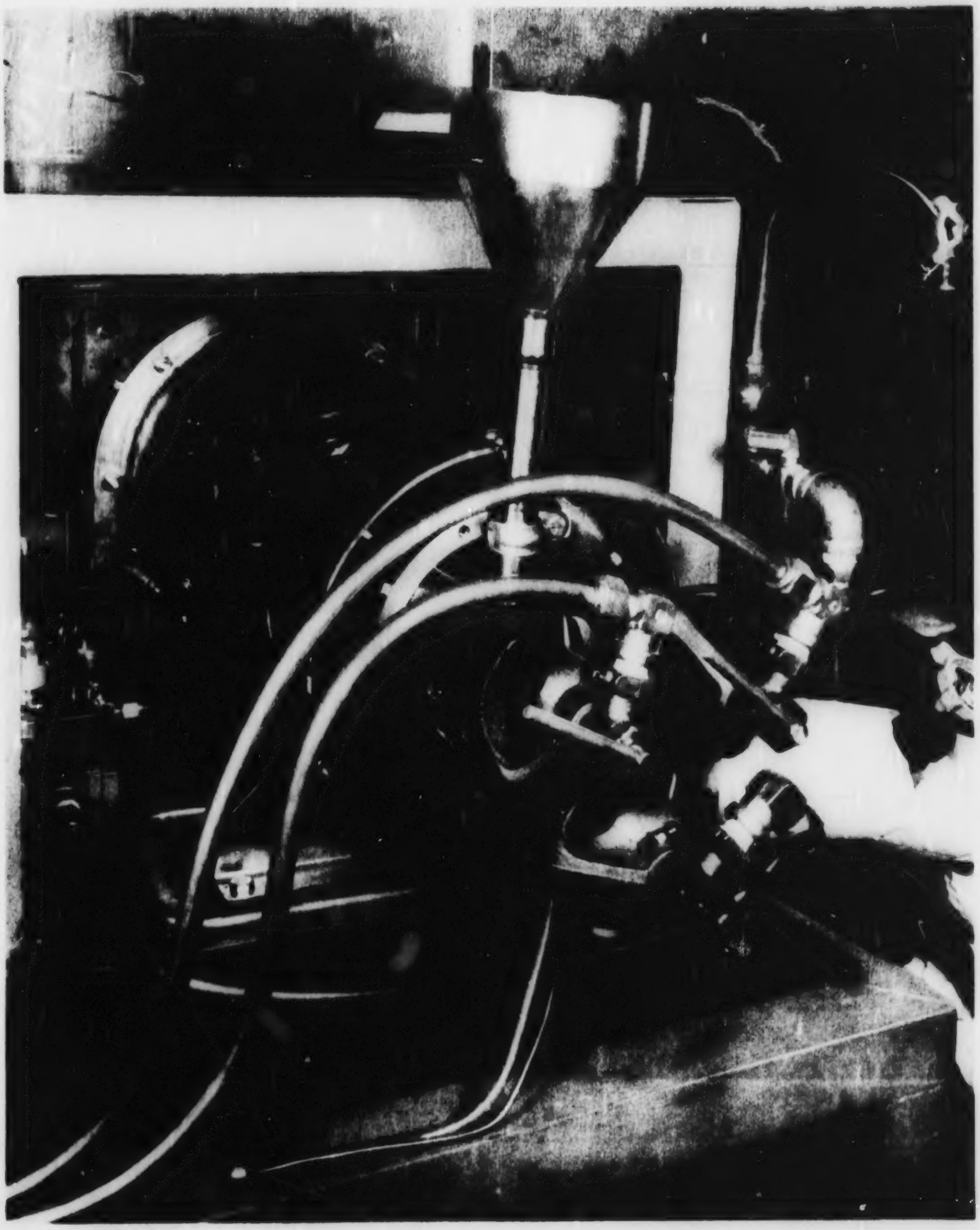


Figure 4. Gas Burner Assembly

irrigating the collecting electrodes, and with and without the insulator heaters energized. Normal current-voltage relationships were obtained with and without electrode irrigation when the insulator heaters were connected to the AC power source through an isolation transformer. Without the transformer, sparking occurred to the epoxy insulator surfaces at relatively low voltage. A typical voltage-current curve is shown in Figure 5. Electrode irrigation causes the V-I curve to shift to the left. Normally, increasing the water vapor content of an air-water vapor mixture would be expected to shift the V-I curve to the right. The shift toward higher current for a given applied voltage indicated for wet operation in Figure 5 may be caused by leakage paths along the surface of the insulators due to moisture accumulation, or an effective decrease in the wire to plate spacing due to the presence of the electrode irrigation stream in the upper portion of the inter-electrode region.

PARTICULATE COLLECTION EXPERIMENTS

Procedure

A series of particulate collection experiments was conducted for the purpose of determining collection efficiency as a function of particle size under idealized conditions. A liquid-phase aerosol (dioctyl-phthalate or DOP) was chosen for the experiments to eliminate the possibility of reentrainment. The particulate generator consisted of a single atomizer which produced a stable polydisperse aerosol. Electrode irrigation and humidification were not used, and the collected oil droplets drained from the collection electrodes by gravity. The carrier gas was ambient air.

Particle size and concentration measurements at the inlet and outlet of the test unit can be made with either an optical particle counter or with inertial impactors. In order to obtain reliable particle size information with an optical particle counter, however, it is necessary to obtain a calibration curve for the instrument with the aerosol under investigation. An attempt was made to obtain such a curve using a vibrating orifice particle generator. However, due to problems with the particle generator, we were unsuccessful in obtaining a useful calibration curve over the particle size range of interest. Therefore, it was decided to conduct the majority of the experiments using impactors to determine particle size distributions and fractional efficiencies. A small number of experiments were conducted using a Climet-Ortec particle size analyzer and a calibration curve obtained with polystyrene latex beads. These measurements are compared with those made with the impactors in a subsequent portion of this section.

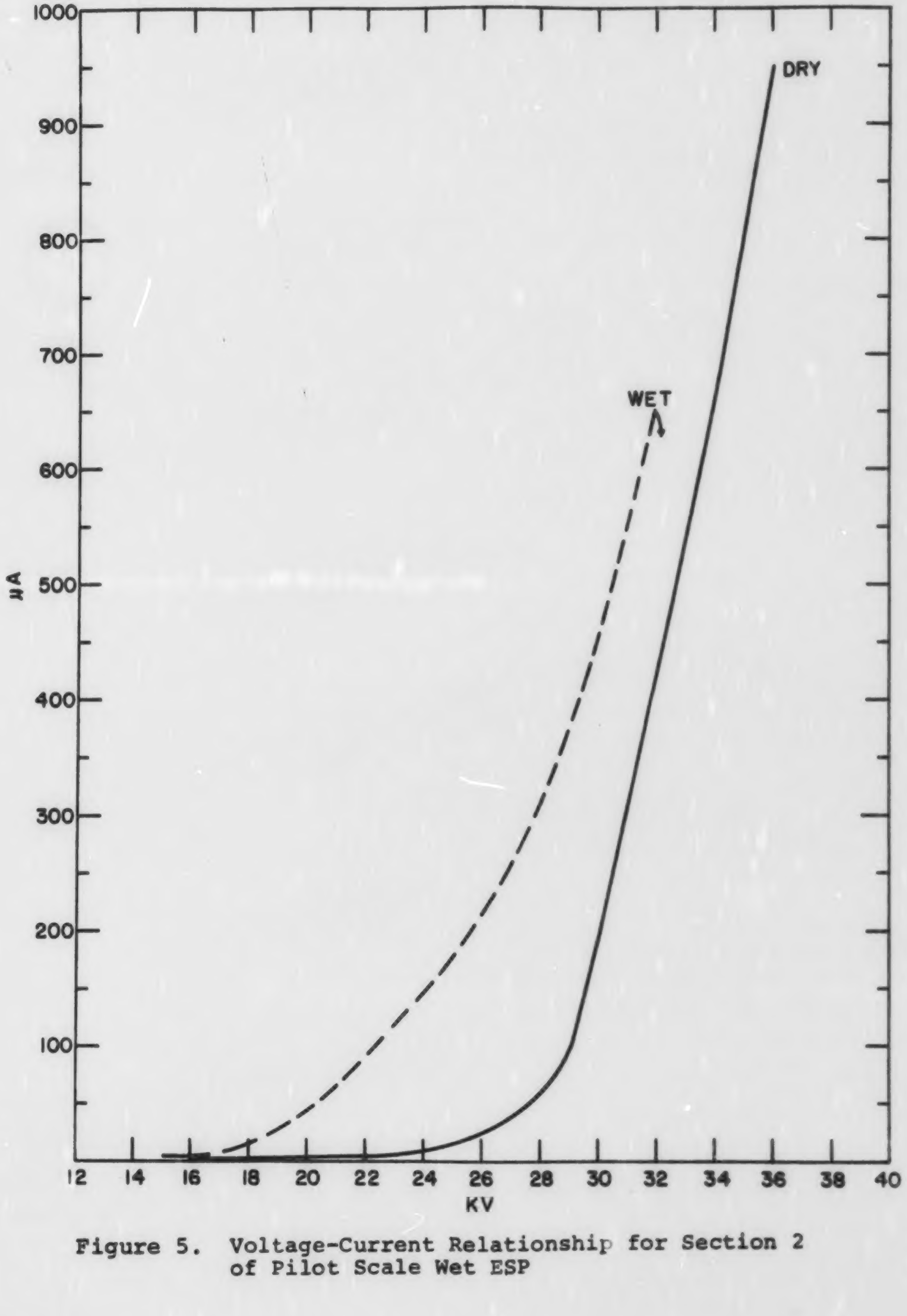


Figure 5. Voltage-Current Relationship for Section 2 of Pilot Scale Wet ESP

A five-stage Brink impactor was used at the precipitator inlet and outlet. Aluminum foil substrates were employed to facilitate weighing of the small masses collected on the individual stages, and the mass determinations were made with a Cahn Electrobalance. For the experiments conducted at the lower gas velocity, a sampling time of six hours was required at the precipitator outlet to obtain weighable quantities on the impactor substrates. Six and four point traverses were conducted with the impactor at the inlet and outlet, respectively, in order to insure that a representative size distribution was obtained at each location.

Since the particulate from an electrostatic precipitator will have an electrical charge, it was necessary to employ a charge neutralizer at the inlet of the sampling line for all measurements made at the precipitator outlet. Measurements with the optical particle counter indicated that, if metal substrates were used in the impactor, the charge acquired by the particulate substantially influenced the size distribution obtained with the impactor. Since the impactor was calibrated with an uncharged aerosol, the use of the charge neutralizer minimized sizing errors due to electrostatic attraction.

Table 1 gives a typical set of inlet and outlet data obtained from duplicate experiments at the indicated conditions. Good reproducibility was obtained for all stages at the inlet, and for stages 2 through 5 at the outlet. Isokinetic sampling was not employed, since the effect of anisokinetic conditions on particles with diameters less than 2.0 μm is expected to be negligible. The effect of changing the gas flow rate through the impactor on the indicated size distribution was checked by reducing the flow rate from 56.6 cm^3/sec to 28.3 cm^3/sec. The higher flow rate, which was used for all of the fractional efficiency determinations, resulted in a gas velocity of 0.79 m/sec at the sample point. Figure 6 shows the inlet size distributions from Table 1 and the distribution obtained at the same location with the reduced impactor flow rate. These data indicate that the same size distribution is obtained at either flow rate. The higher flow rate is more desirable because of the smaller cut points and the increased amount of gas that may be sampled per unit time.

Results

Fractional efficiency measurements were performed with the Brink impactor and DOP aerosol at current densities of 26.9, 53.8, and 107.5 nA/cm^2 at a gas velocity of 1.37 m/sec, and at current densities of 26.9 and 53.8 nA/cm^2 at a gas velocity of 0.72 m/sec. The results obtained from these experiments, expressed as collection efficiency as a function of particle diameter, are presented in Figures 7, 8, and 9. Computed collection efficiencies obtained with a mathematical model are also shown.[1] In view of the difficulties in making these types of measurements, the agreement between measured and calculated efficiencies shown in Figure 7 is considered good. Figures 8 and 9 suggest that

TABLE I

TYPICAL INLET AND OUTLET PARTICLE SIZE DATA FOR WET ESP EXPERIMENTS
(DOP Sprayer, Gas Velocity = 1.37 m/sec, Current Density = 55 na/cm^2)

		Mass Loading, mg/am^3									
		Inlet					Outlet				
Test No.		2ai	2bi	2ci	2di	Average	2ao	2bo	Average	Geometric Mean Diameter, μm	Collection Efficiency, %
Stage	Lower Diameter Limit, μm										
1	3.04	26.341	28.956	24.596	24.088	25.995	0.0414	$\sim$0	0.207	-	-
2	1.80	18.659	13.526	14.120	15.226	15.385	0.1494	0.1103	0.1299	2.34	99.16
3	1.24	7.249	6.285	7.238	8.226	7.250	0.2575	0.2115	0.2345	1.49	96.77
4	0.65	7.448	6.984	6.743	7.419	7.148	0.5724	0.4782	0.5253	0.90	92.65
5	0.46	2.954	1.775	2.514	2.654	2.474	0.3862	0.3770	0.3816	0.55	84.58

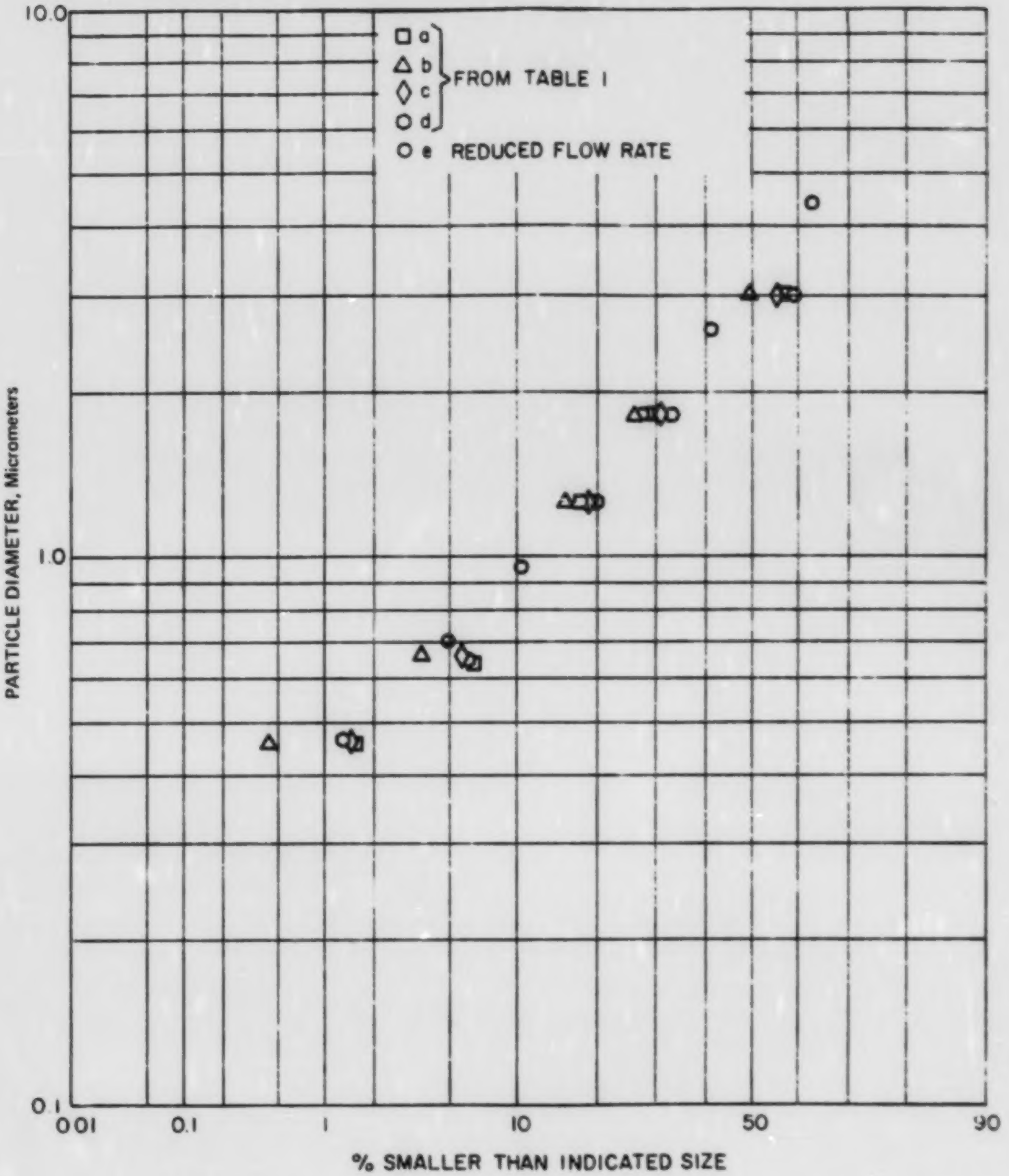


Figure 6. Inlet Particle Size Distributions from Brink Impactor Data

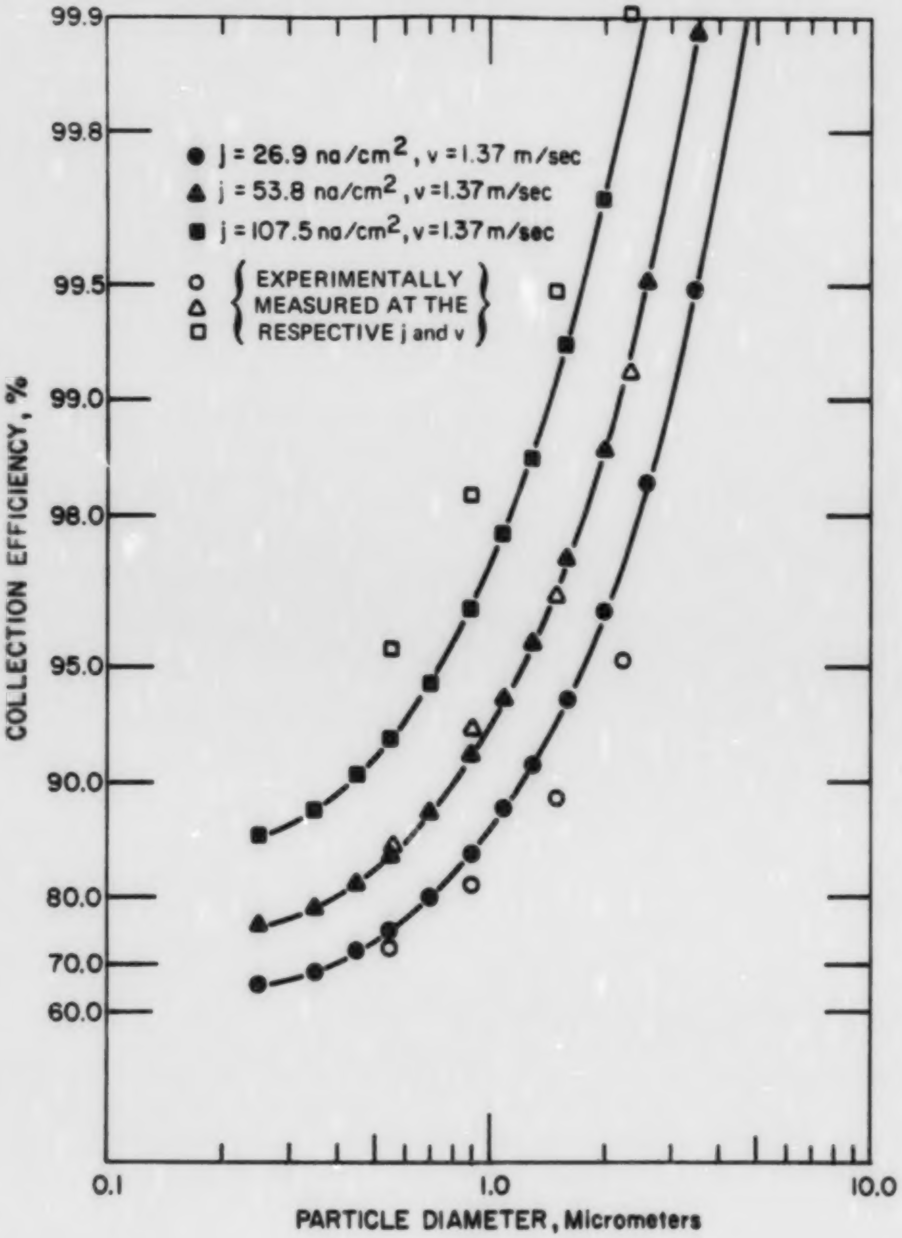


Figure 7. Experimentally Measured and Ideally Calculated Fractional Collection Efficiencies in the Laboratory Precipitator

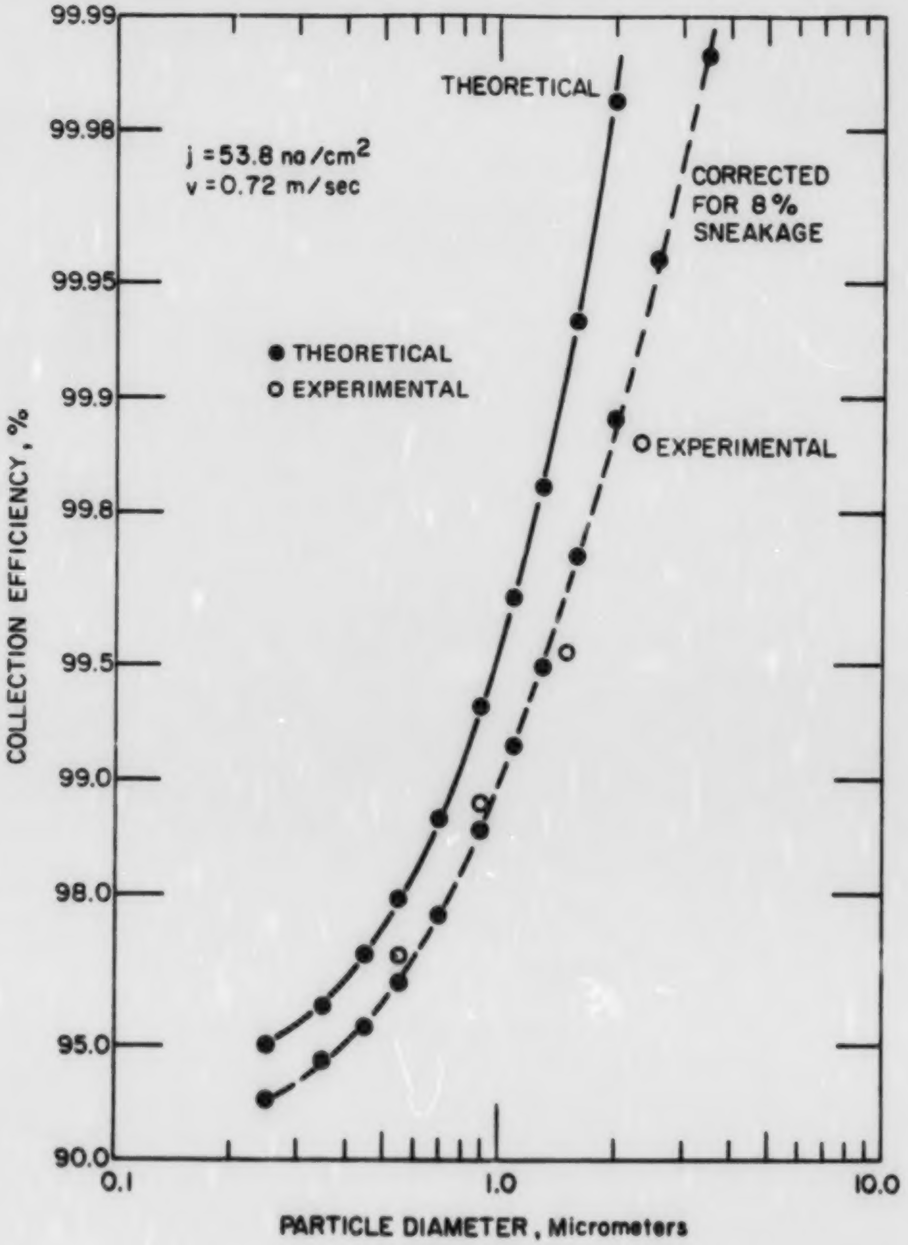


Figure 8. Experimentally Measured, Ideally Calculated, and Sneakage-Corrected Fractional Collection Efficiencies for a Current Density of 53.8 nA/cm^2 and a Gas Velocity of 0.72 m/sec in the Laboratory Precipitator

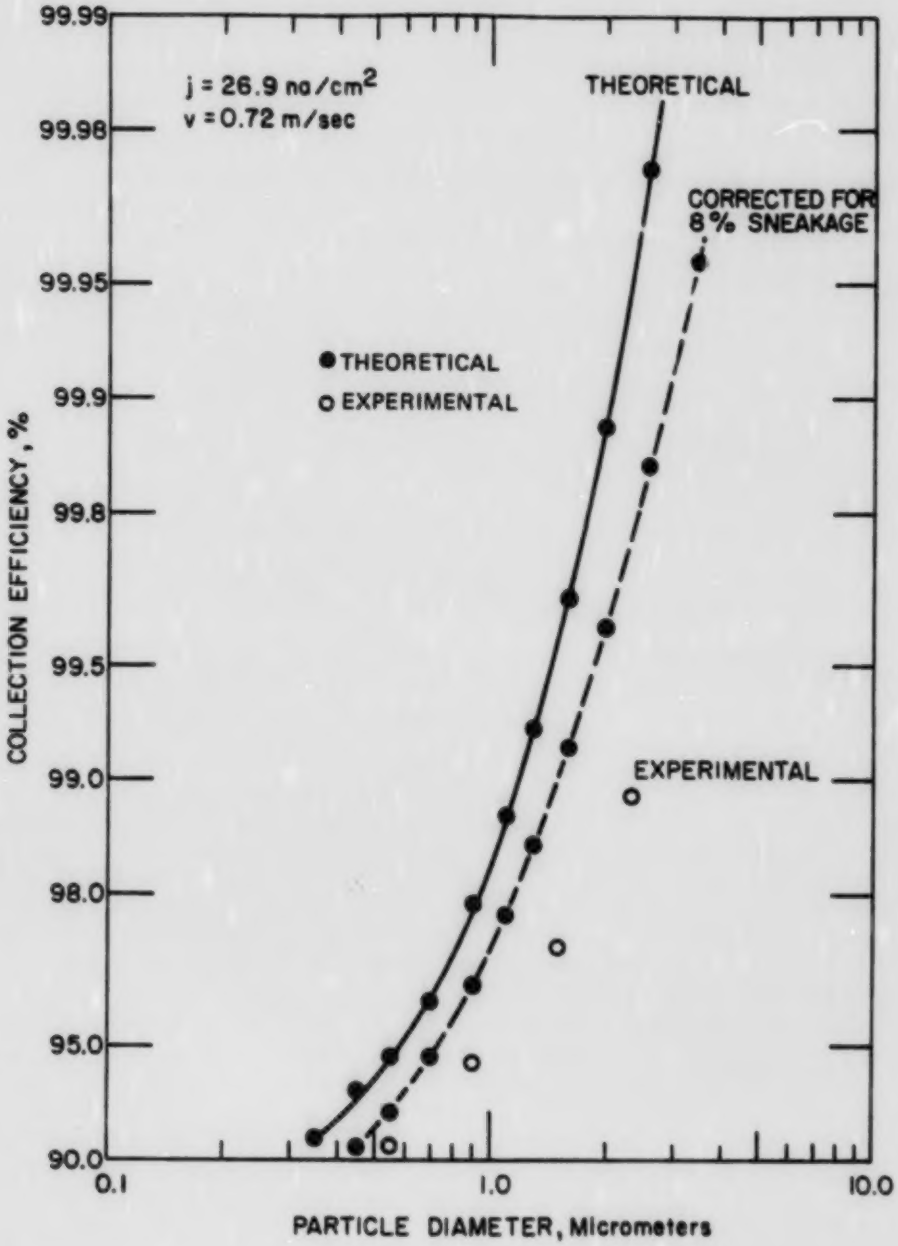


Figure 9. Experimentally Measured, Ideally Calculated, and Sneakage-Corrected Fractional Collection Efficiencies for a Current Density of 26.9 nA/cm^2 and a Gas Velocity of 0.72 m/sec in the Laboratory Precipitator

the agreement obtained between computed and measured results worsens with decreasing current density. The assumption of 8% gas sneakage over four stages improves agreement between computed and measured results at a gas velocity of 0.72 m/sec. However, the data obtained at this lower gas velocity with 26.9 nA/cm^2 are considerably below the computer projections. Possible causes for this lack of agreement are unmodelled effects such as non-uniform current density and electric field, and particle concentration gradients in the interelectrode space.

The performance of an electrostatic precipitator for monodisperse particles may be expressed in terms of an effective migration velocity, defined by

$$w_e = \frac{Q}{A} \ln \left(\frac{100}{100-\eta_i}\right) ,$$

where

w_e = effective migration velocity of the particle size under consideration, cm/sec

Q/A = ratio of volume flow to plate area, m^3/sec/m^2

η_i = collection fraction of the particle size under consideration.

Figures 10, 11, and 12 give effective migration velocities obtained from the efficiency data in Figures 7, 8, and 9.

Figure 10 indicates good agreement between the computed and experimentally derived values of effective migration velocity. The assumption of 8% sneakage over four stages improves agreement between the computed and experimental results only for the lowest current density. Figure 11 indicates that, at the lower gas velocity of 0.72 m/sec, the correction for 8% by-passage gives agreement with the experimental results. At 26.9 nA/cm^2 and 0.72 m/sec, however, Figure 12) the experimentally derived values for effective migration velocity are between 7.7 and 25.5% lower than the corrected computed values. Due to the degree of uncertainty in the data, additional experiments are needed for definite conclusions regarding confidence limits for the model predictions. However, these comparisons suggest that, although the model closely approximates the experimental results, it tends to overpredict performance at lower values of current density and gas velocity, and underpredict performance for the highest value (107.5 nA/cm^2) of current density.

Additional work is planned under EPA support to evaluate the model predictions with varying electrode geometries and operating conditions.

Figure 13 is a comparison of results obtained with the Brink impactor and with a Climet-Ortec particle size analyzer. The particle size information obtained with the Climet-Ortec is based on a calibration curve obtained with polystyrene latex beads (PSL). Since the measurements obtained with the Climet

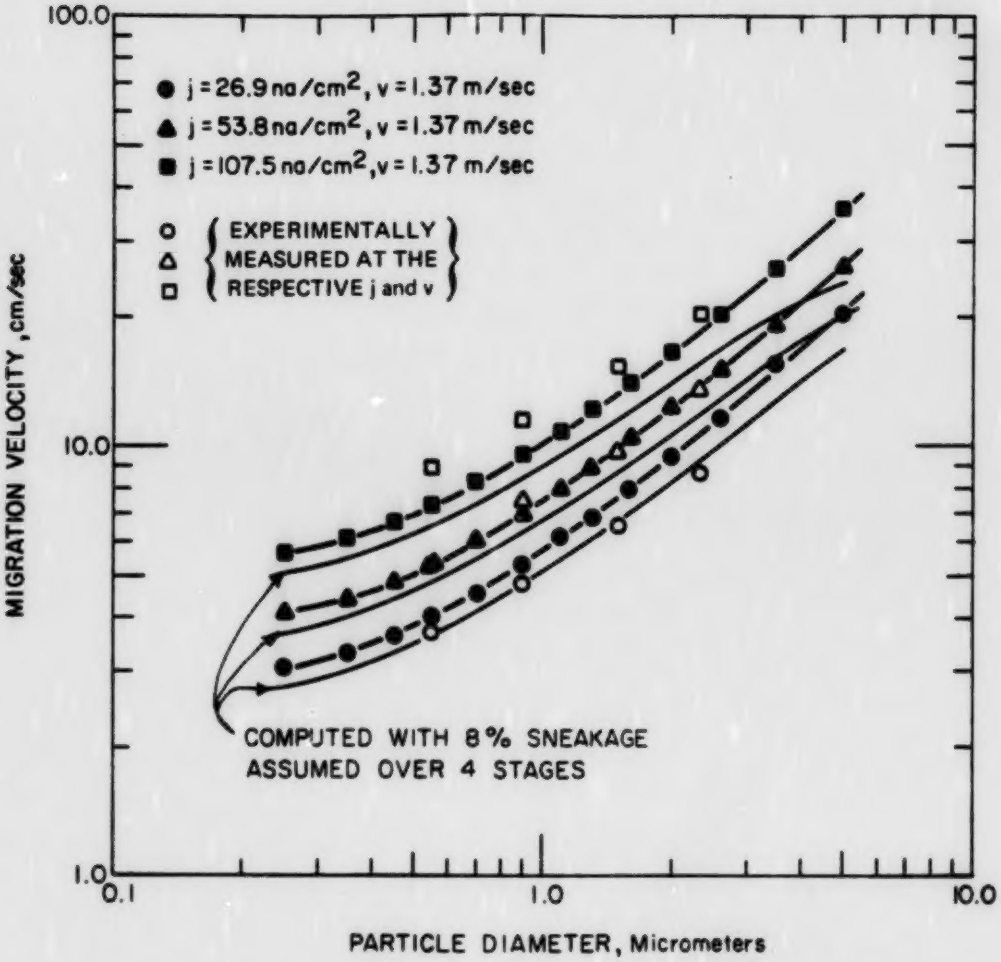


Figure 10. Experimentally Measured, Ideally Calculated, and Sneakage-Corrected Migration Velocities as a Function of Particle Size in the Laboratory Precipitator

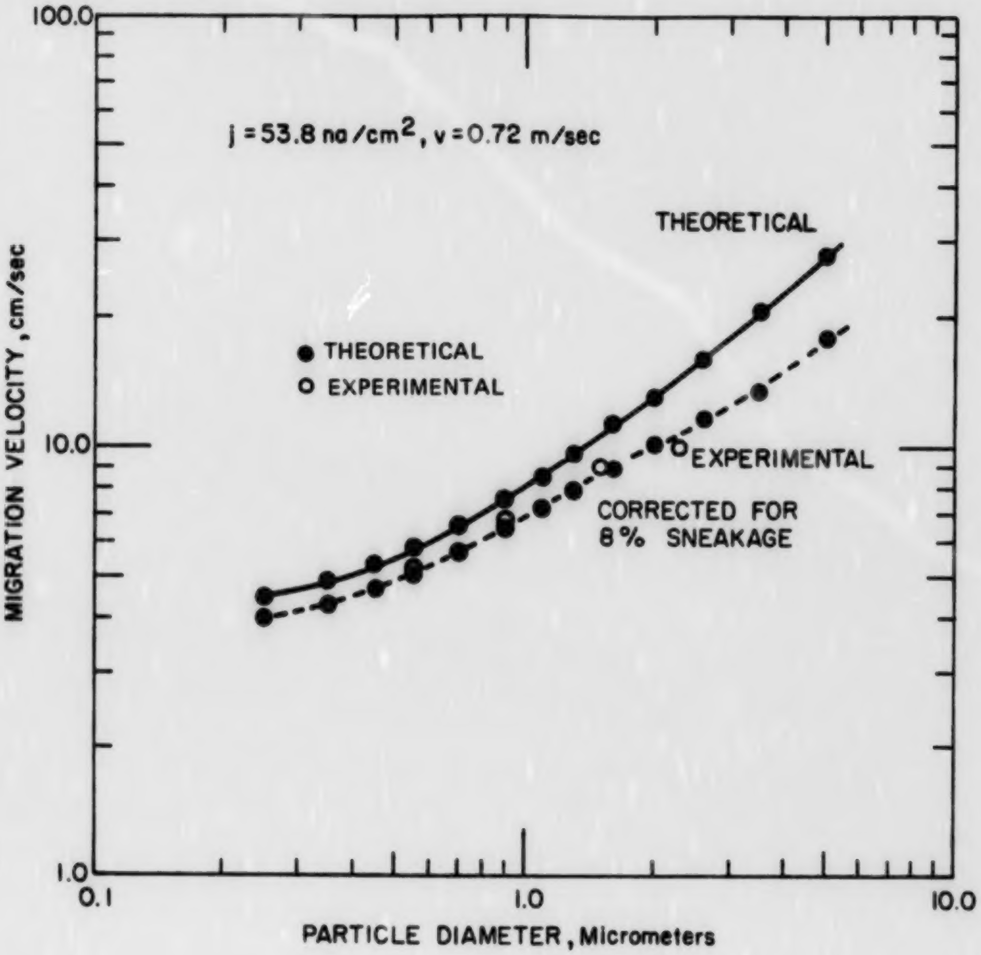


Figure 11. Experimentally Measured, Ideally Calculated, and Sneakage-Corrected Migration Velocities as a Function of Particle Size for a Current Density of 53.8 nA/cm^2 and a Gas Velocity of 0.72 m/sec in the Laboratory Precipitator

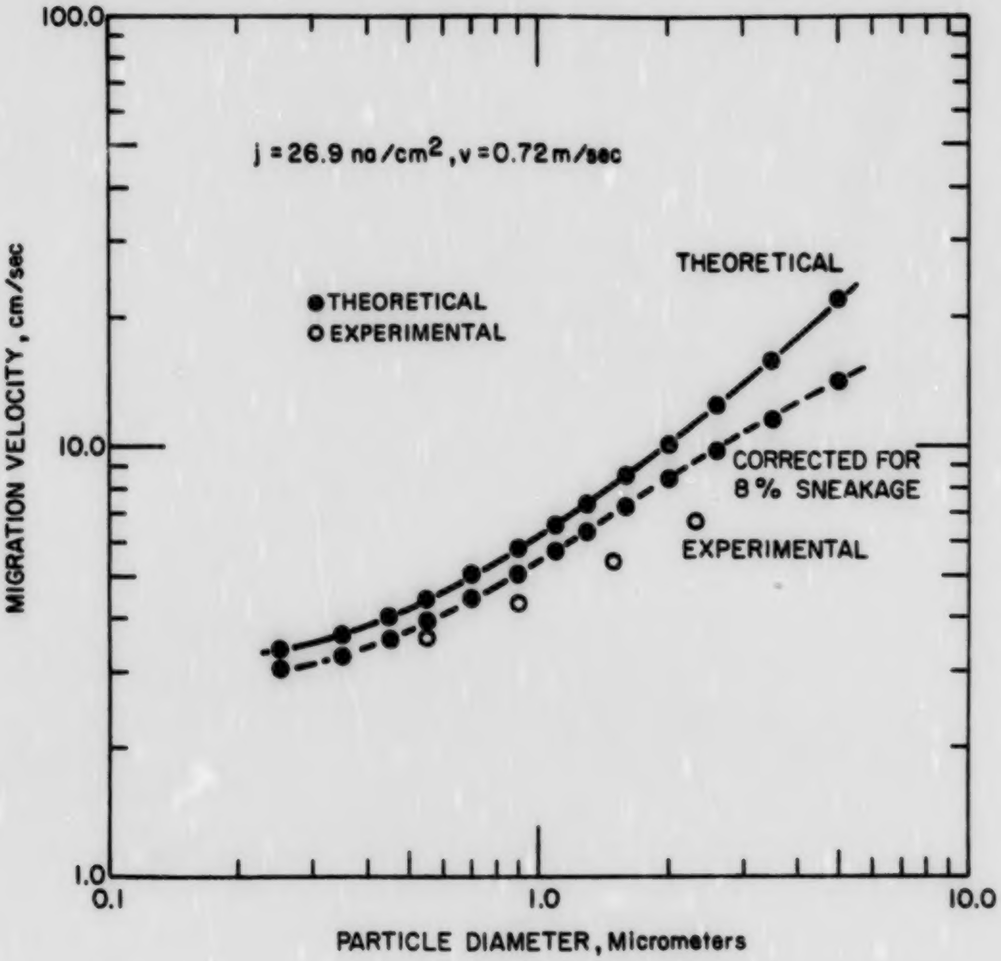


Figure 12. Experimentally Measured, Ideally Calculated, and Sneakage-Corrected Migration Velocities as a Function of Particle Size for a Current Density of 26.9 nA/cm² and a Gas Velocity of 0.72 m/sec in the Laboratory Precipitator

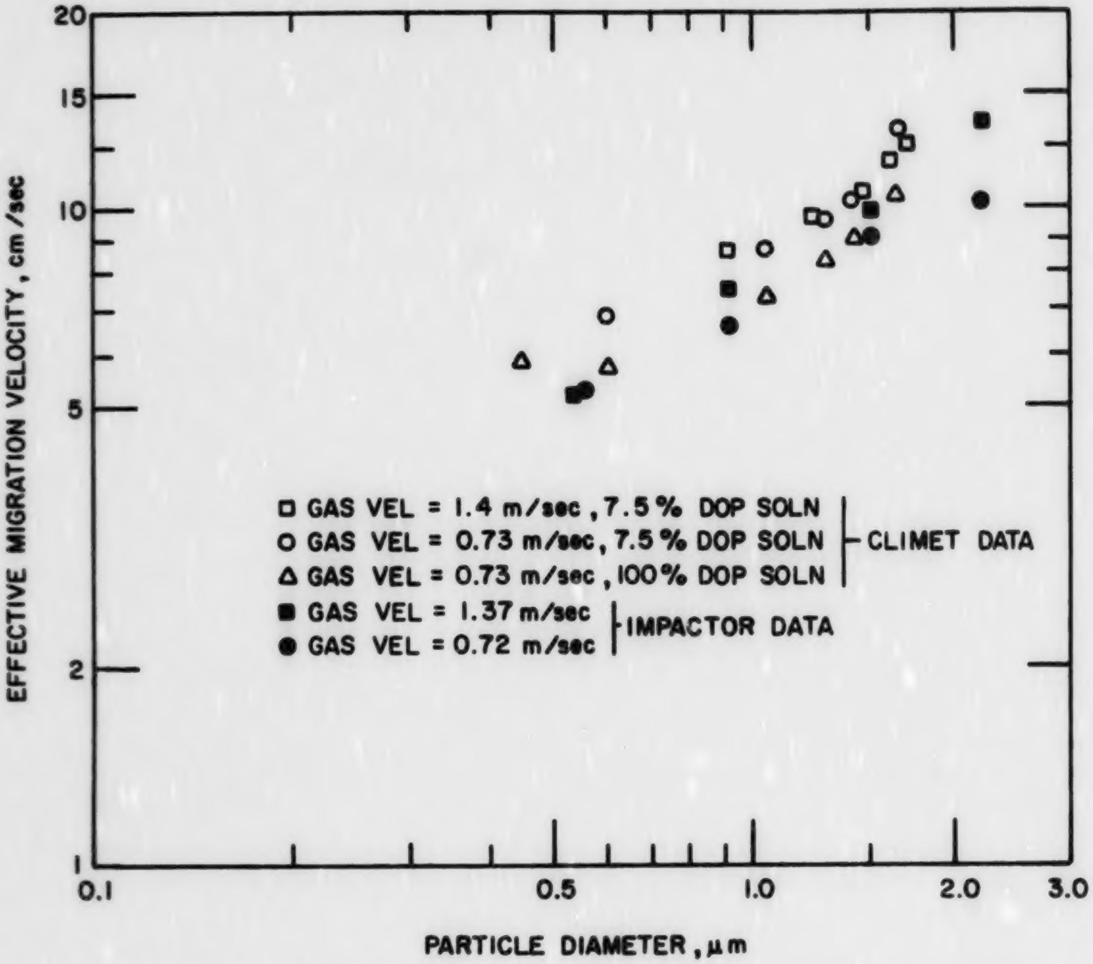


Figure 13. Effective Migration Velocities from Climet and Brink Efficiency Determination with DOP Particulate at 50 na/cm^2.

were accomplished with the use of a diluter with an intake several seconds in residence time downstream from the aerosol generator, the concentration of DOP in the solution used for the particle generator should not have an influence on the indicated particle sizes. The comparison in Figure 13 indicates fair agreement between effective migration velocities derived from measured efficiencies obtained with the Climet-Ortec and with the impactor. This suggests that the calibration curve obtained for the optical instrument with PSL is also reasonably accurate for a DOP aerosol.

SULFUR OXIDE AND PARTICULATE COLLECTION EXPERIMENTS

Since wet precipitator-scrubber systems have been proposed for removing particulate and sulfur oxides from stack gases, it is of interest to examine the simultaneous removal of DOP particulate and SO_2 in the laboratory test unit. Section V will present calculations which indicate that no significant additional SO_2 removal should be anticipated in a wet ESP due to the presence of a corona current and an electric field. The experiments reported in this section were limited in scope and were conducted primarily for the purpose of determining the validity of this conclusion.

The wet precipitator test unit was equipped with a positive displacement metering pump and a static mixer for metering and mixing a concentrated solution of sodium hydroxide into the water used for irrigating the collection electrodes. Sulfur dioxide was metered from a gas cylinder into the test unit upstream from the mixing chamber. Ambient air was used as the carrier gas at a flow velocity of 0.76 m/sec and the SO_2 was fed at a rate which resulted in a concentration of about 2000 parts per million by volume. The liquid to gas ratio was held constant at 2.8 l/m^3 (20.7 gal/1000 ft^3), and the residence time of the gas in the irrigated and electrified region was about four seconds.

The following groups of experiments were conducted:

1. The SO_2 removal efficiency of the device was determined with only H_2O irrigating the electrodes with the electrified sets deenergized.

2. The SO_2 removal efficiency was determined with NaOH solution irrigating the electrodes with the electrical sets deenergized.

3. The SO_2 and particulate removal efficiency was determined using DOP particulate with NaOH solution irrigating the electrodes with the electrical sets energized.

The SO_2 removal efficiencies obtained in these experiments are given in Table 2. The molar ratio of NaOH to SO_2 entering the test unit was 2.68 to 1 for experimental groups 2 and 3; therefore, the degree of removal in these experiments is governed by mass transfer dynamics instead of chemical equilibria. Mass transfer calculations that will be discussed in Section V indicate that only a small portion of the absorption shown in Table 2 can be accounted for by the area of the collecting electrodes, and that electrical transport of SO_2 would be expected to have a negligible effect on the overall SO_2 removal efficiency. The major portion of the SO_2 absorption in these experiments was apparently achieved by droplets generated by the electrode irrigation manifolds. Table 2 shows that the SO_2 absorption decreased for the experiments conducted with DOP particulate undergoing collection. It is hypothesized that the indicated decrease of SO_2 uptake was caused by a noticeable decrease in the wettability of the collection electrodes resulting from the collection of oil droplets on the electrodes.

These limited experiments tend to confirm the hypothesis that electric fields and corona current do not significantly improve the SO_2 uptake capability of a wet ESP simultaneously collecting particulate and SO_2. Unfortunately, the conclusion is clouded somewhat by the decrease in absorption area caused by the DOP particulate. It may be argued, however, that plate wettability is also likely to decrease under practical operating conditions due to residual material remaining on the plates.

Particulate collection efficiencies were measured with the Climet-Ortec particle size analyzer during the SO_2-DOP particulate experiments. Effective migration velocities calculated from these efficiencies are presented in Figure 14, and the applied voltages for the "dry" and "wet" particulate collection experiments at a current density of 50 $\mu A/ft^2$ are given in Table 3. A comparison of the data in Figures 13 and 14 indicate that the particulate collection performance of the test unit was not affected, within the uncertainty of the measurement techniques, by the presence of SO_2 and the use of electrode irrigation.

TABLE 2

SO_2 REMOVAL EXPERIMENTS

Experiment Group No. (see text)	SO_2 Outlet Concentration ppm by volume	[1]SO_2 Removal Efficiency %
(1)	1300	34.3
	1379	30.3
	1326	33.0
(2)	1015	48.7
	960	51.5
	1024	48.3
(3)	1172	40.8
	1109	44.0

1. Average inlet concentration = 1979 ppm

TABLE 3

APPLIED VOLTAGE IN WET ESP , TEST UNIT AT 50 μA/ft² CURRENT DENSITY

	kV	
Power Supply No.	Dry Walls, Ambient Air, DOP Particulate	Wet Walls, Ambient Air & SO_2, DOP Particulate
1	33	25
2	32	33
3	31.5	31

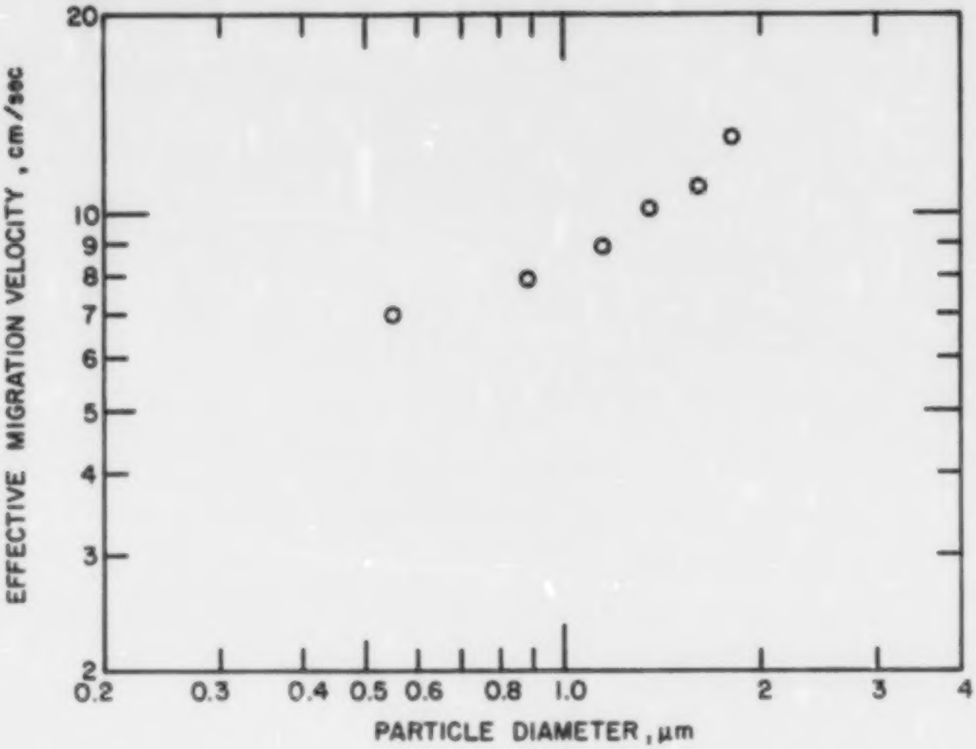


Figure 14. Effective Migration Velocities for SO_2 - DOP Particulate Experiment (gas Velocity = 0.76 m/sec).

SECTION IV
EVALUATION OF FULL-SCALE WET ELECTROSTATIC PRECIPITATOR INSTALLATIONS

FIELD TEST MEASUREMENTS

Introduction

Fractional and overall particulate collection efficiency measurements were made on a plate-type wet electrostatic precipitator collecting fume from an aluminum pot line consisting of horizontal stud self-baking aluminum reduction cells. These measurements were conducted under another contract and reported in detail elsewhere.[2] Comparisons were made between measured (with Andersen impactors) and predicted collection efficiencies obtained from a mathematical model of an electrostatic precipitator.

Figure 15 shows the arrangement of the unit on which the test series was conducted, and Figure 16 is a schematic of the liquor flow through the system as given by Bakke.[3]

Measurement Techniques

Particle Sizing -

Particle size and concentration measurements were conducted using the following methods:

1. Diffusional techniques using condensation nuclei counters and diffusion batteries for determining concentration and size distribution on a number basis for particles having diameters less than approximately 0.2 μm.
2. Optical techniques for determining concentrations and size distributions for particles having diameters between approximately 0.3 μm and 1.5 μm. Figure 17 shows the optical and diffusional sizing system.
3. Inertial techniques using cascade impactors for determining concentrations and size distributions on a mass basis for particles having diameters between approximately 0.25 μm and 5.0 μm. Andersen impactors were used simultaneously at the precipitator inlet and outlet. Extremely low mass loadings at the outlet made necessary the operation of the impactors for approximately 16 hours to obtain weighable quantities of particulate.

Mass Loading Measurements -

A modified EPA sampling train with an in-stack filter holder was

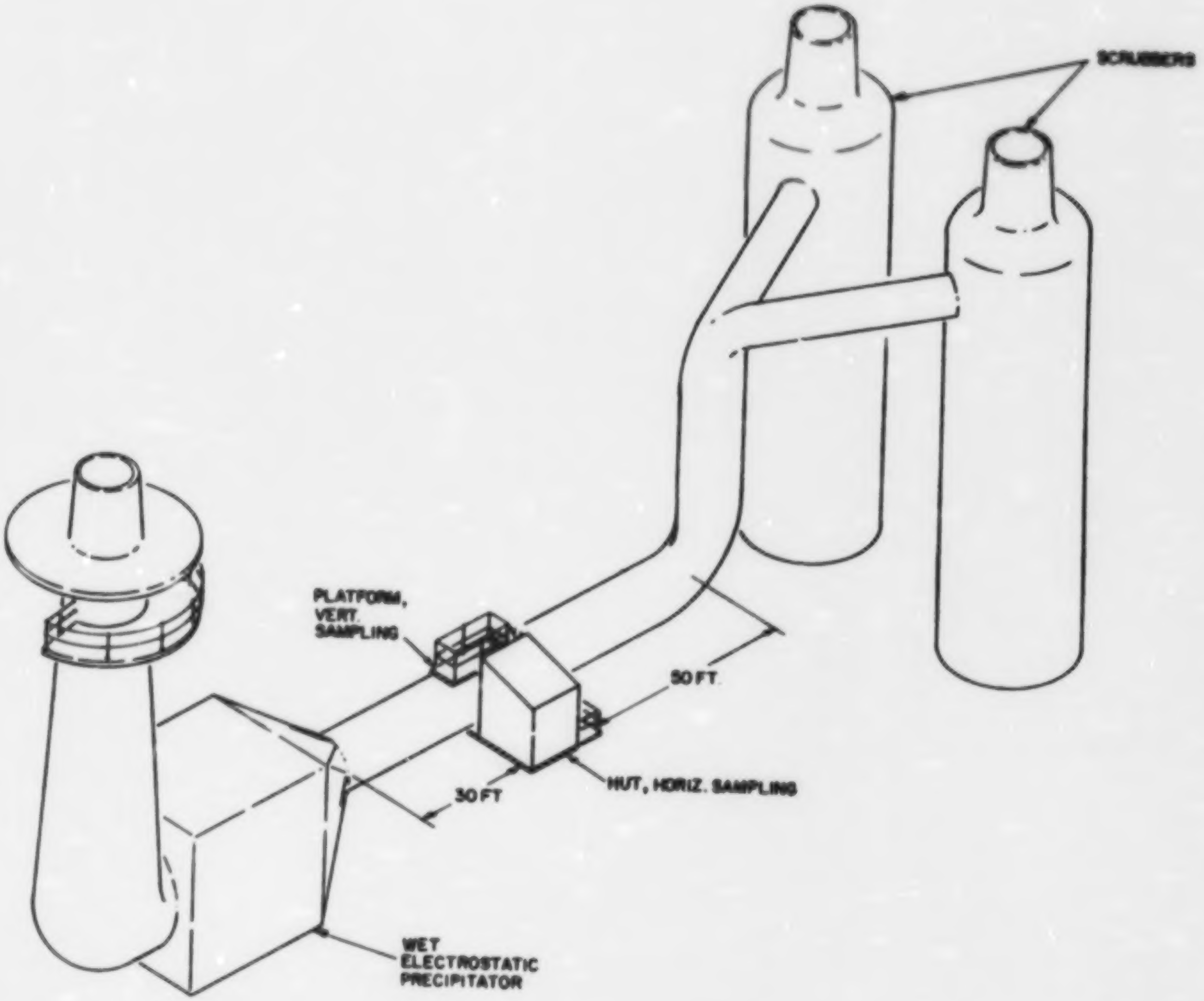

SCRUBBERS
PLATFORM,
VERT.
SAMPLING
50 FT.
30 FT
HUT, HORIZ. SAMPLING
WET
ELECTROSTATIC
PRECIPITATOR

Figure 15. Schematic of scrubber-precipitator system and sampling locations

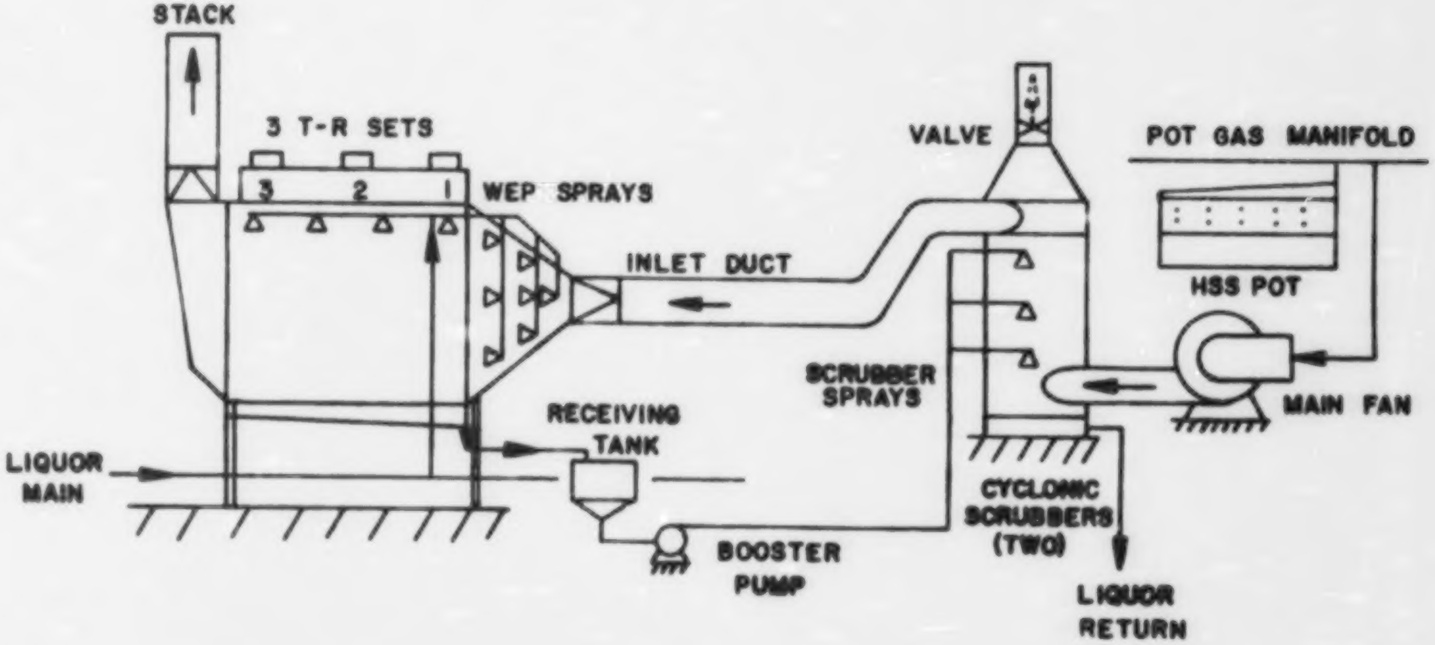

STACK
3 T-R SETS
3
2
1
WEP SPRAYS
INLET DUCT
VALVE
POT GAS MANIFOLD
HSS POT
MAIN FAN
SCRUBBER SPRAYS
RECEIVING TANK
LIQUOR MAIN
BOOSTER PUMP
CYCLONIC SCRUBBERS (TWO)
LIQUOR RETURN

Figure 16. Schematic of primary emission control system [1]

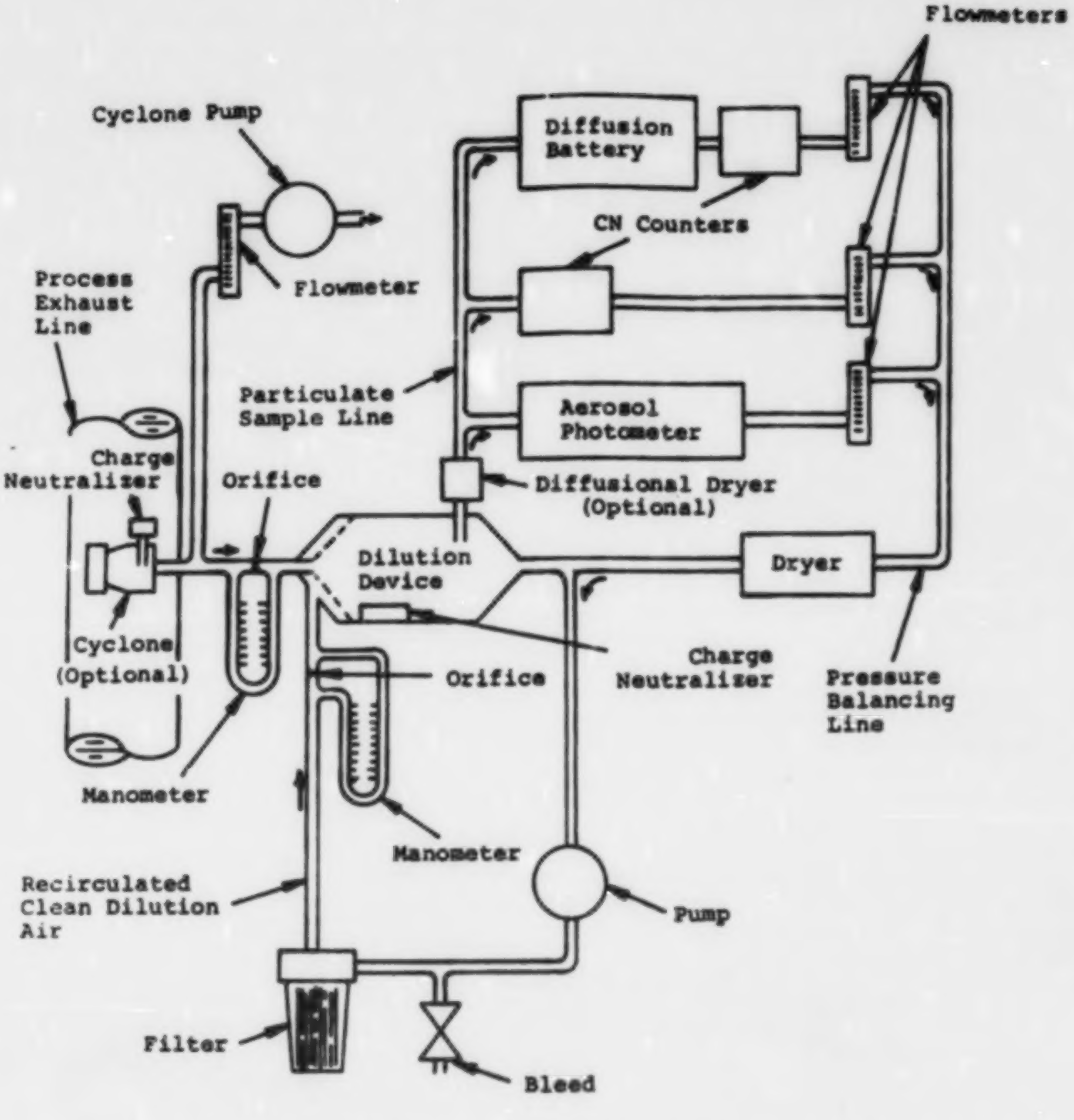

Flowmeters
Cyclone Pump
Diffusion Battery
CN Counters
Flowmeter
Process Exhaust Line
Particulate Sample Line
Aerosol Photometer
Charge Neutralizer
Orifice
Diffusional Dryer (Optional)
Dilution Device
Dryer
Cyclone (Optional)
Charge Neutralizer
Orifice
Pressure Balancing Line
Manometer
Manometer
Recirculated Clean Dilution Air
Pump
Filter
Bleed

Figure 17. Optical and diffusional sizing system

used for the mass loading measurements, which were conducted at the inlet and outlet simultaneously with the impactor runs. An isokinetic traverse across the stack was conducted at both the precipitator inlet and outlet through a single sampling port at each location except for the last day, when a single point mass determination was performed at the outlet.

Results

The mass median diameters of both inlet and outlet distributions as determined by the Andersen impactors are less than 1.0 μm. Figure 18 presents the Andersen data on log probability coordinates.

Figure 19 gives the cumulative size distribution on a number basis for this test series and various other industrial particulate sources as measured by optical and diffusional methods. Fractional efficiencies were computed from the optical and diffusional data, based on inlet measurements conducted on August 20 and 21, and outlet measurements conducted on August 22 and 23, 1974. Figure 20 gives the results of these calculations, together with the inertially determined fractional efficiencies. A theoretically calculated fractional efficiency curve is also given, and this will be discussed later.

Mass Loading Measurements -

Mass train measurements were performed by Guardian Systems, Inc. of Birmingham, Alabama, under subcontract to Southern Research Institute and these results are given in Table 4. Fair agreement was obtained between the total mass loading with Andersen impactors and the mass train at the inlet, but severe disagreement occurred at the outlet.

The total mass obtained with a traverse using the mass train at the outlet was greater than that collected with the impactors by a ratio of approximately 5 to 1. When the mass filter was operated near the center of the stack and near the sampling location used for the impactors, the disagreement was reduced to a ratio of about 3 to 1. A comparison of outlet loadings however, indicates that the mass train results obtained during this test series are in fair agreement with those obtained previously by a local pollution control agency. Both the Andersen data and the mass data showed good reproducibility.

It is our conclusion that the most probable cause of the mass loading discrepancy is the collection of large water droplets containing solids by the mass filter. Such droplets would be subject to stratification in the stack, and this is qualitatively indicated by the decrease in loading which occurred when the mass train was operated at a single point. Additional work with a

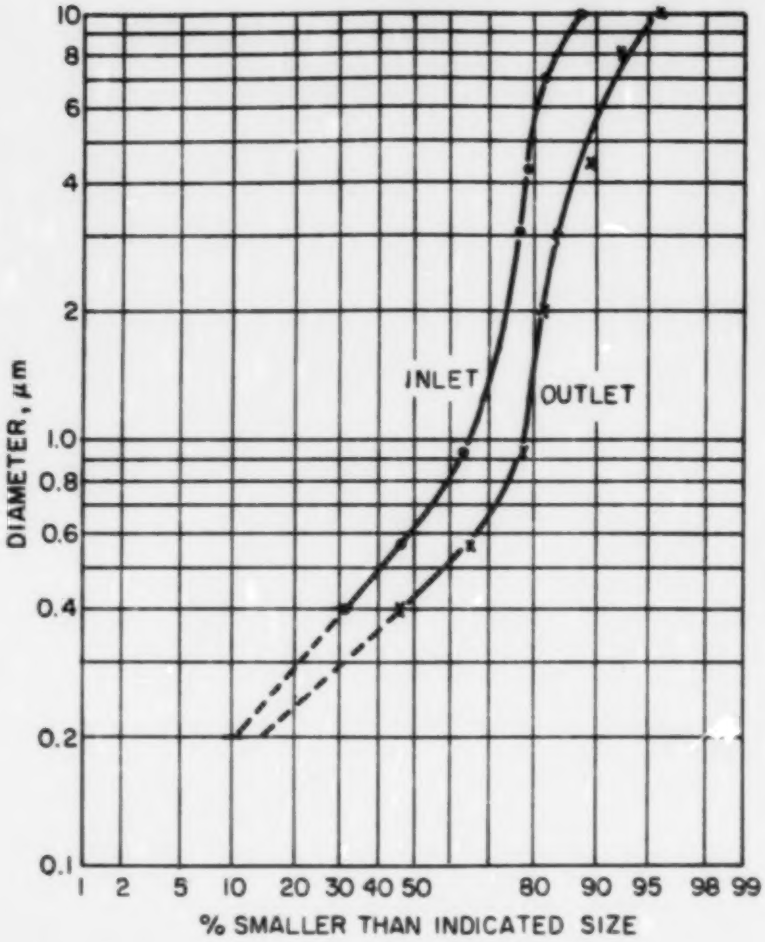


Figure 18. Andersen data on log probability co-ordinates

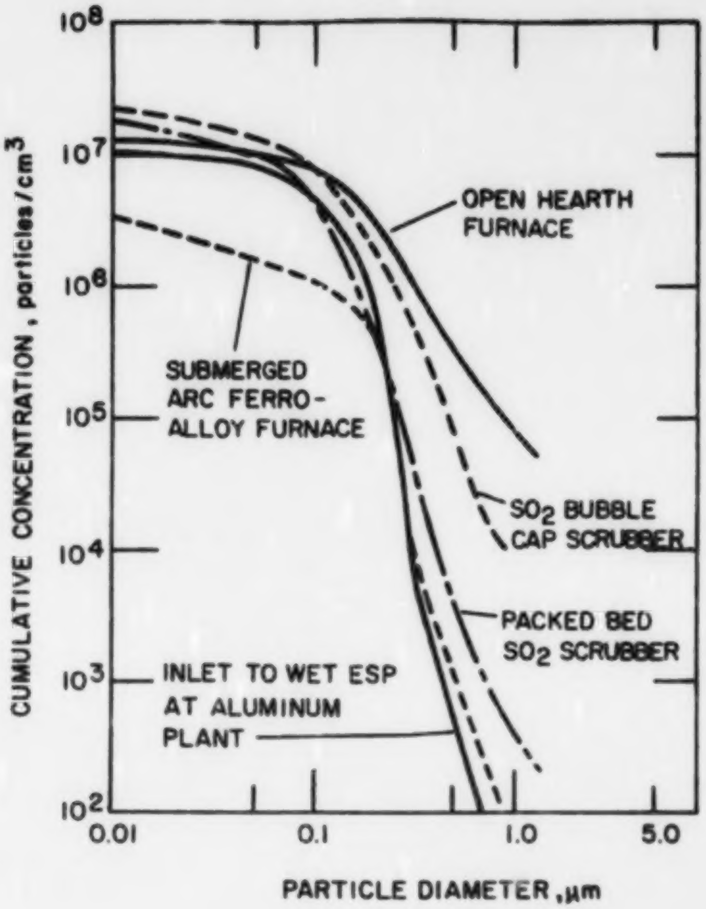


Figure 19. Cumulative size distributions on a number basis for various industrial particulate sources as measured by optical and diffusional methods

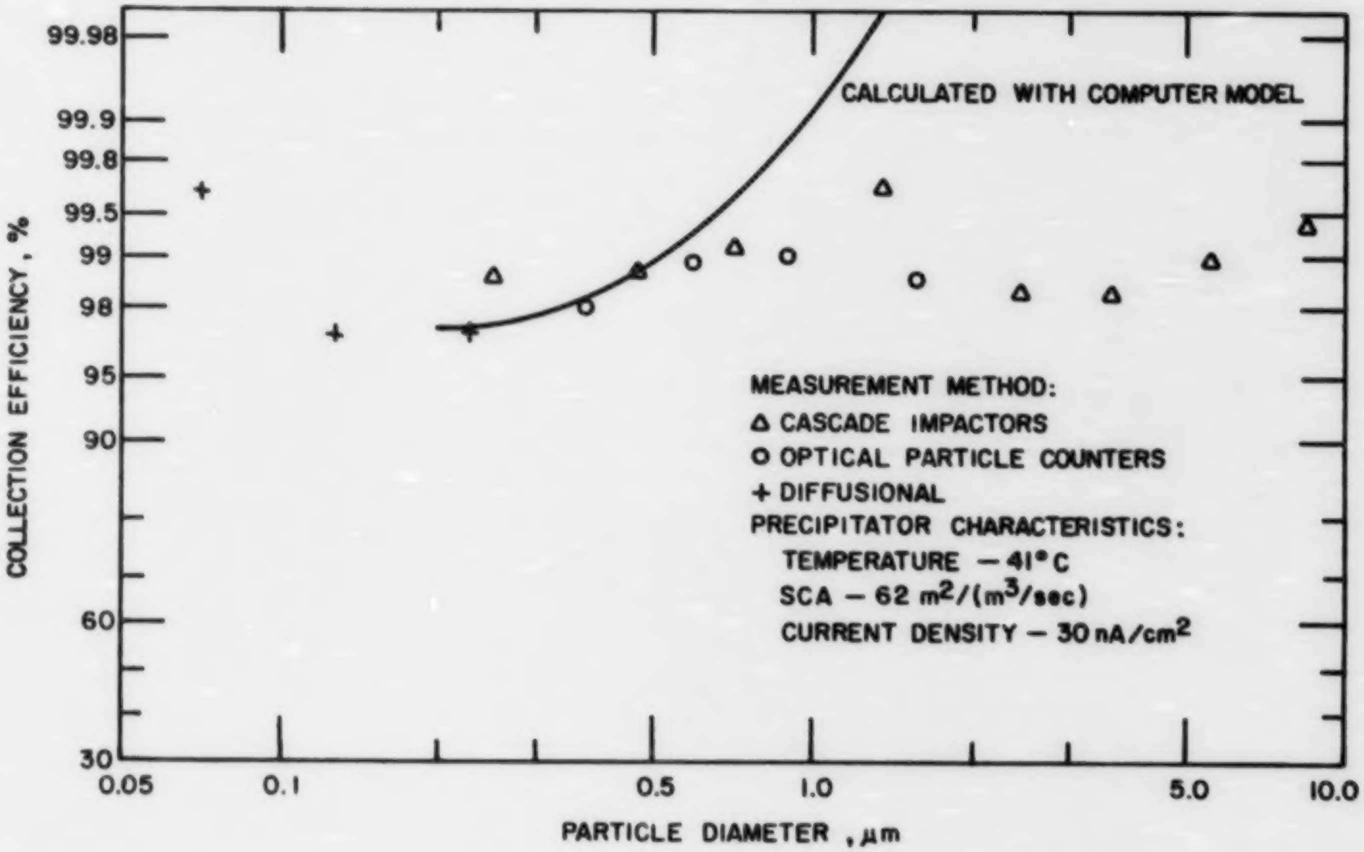


Figure 20. Measured fractional efficiencies for a wet electrostatic precipitator with the operating parameters as indicated, installed downstream of a spray type scrubber on an aluminum reduction pot line.

Table 4. MASS TRAIN TEST RESULTS - 553 WET ESP

	Inlet				Outlet			
Run No.	1	2	3	4	1	2	3	4[4]
Date	8/20	8/21	8/22	8/23	8/20	8/21	8/22	8/23
Sampling Time, min.	300	250	280	310	376	375	375	360
H_2O, % by vol in gas	5.09	4.91	5.45	6.03	5.19	4.96	5.22	5.95
Avg. Gas Temp., °C	40.9	40.9	40.9	40.9	[2]34.2	38.1	38.1	38.1
[1]Flow, am^3/sec	67.2	62.5	54.9	62.5	44.6	43.5	44.4	43.9
[3]Flow, DN m^3/sec	55.4	51.7	45.1	51.1	37.6	36.3	36.9	36.3
mg/am^3	89.0	94.5	95.7	100.9	4.58	4.26	3.57	1.97
gr/acf	0.0389	0.0413	0.0418	0.0441	0.00200	0.00186	0.00156	0.00086
gr/Dscf	0.0443	0.0449	0.0476	0.0494	0.00220	0.00209	0.00166	0.00098
Efficiency, %					95.03	95.34	96.51	98.02

Notes:
1. Based on traverse across one sampling port and area of 3.05 m^2(32.85 ft^2)
2. Based on traverse across one sampling port and area of 3.54 m^2(38.10 ft^2).
3. 0°C and 760 mm Hg.
4. Obtained at a single point near the center of the stack.

traverse using a sampling device designed to provide sizing information above 10 μm diameter would be required to resolve the problem.

Analysis of Results

The wet electrostatic precipitator on which this test series was conducted is a wire and plate design with three electrical sections in series in the direction of gas flow. Plate-to-plate spacing is 30.5 cm (1 ft), and each collecting electrode is 1.83 m long (6 ft) and 7.52 m high (25 ft). Thus, the total parallel plate collecting electrode length is 5.48 m, or 18 ft. Each electrical set powers 28 gas passages. The total parallel plate collecting area is 2342 m^2 (25,200 ft^2), and the "transverse baffles", which are perpendicular to the gas flow, provide additional collecting electrode area. The effective collecting area provided by these baffles was estimated as 390 m^2 (4200 ft^2), resulting in a total collection area of 2732 m^2 (29,400 ft^2). Average specific collecting area during the test series was therefore 62 $m^2/(m^3/sec)$, or 315 $ft^2/(100\ cfm)$.

Electrode irrigation is provided by sprays at the precipitator inlet and above the collection plates. The sprays provide a mist which is collected along with the particulates in the flue gas, and the electrode cleaning is accomplished by the coalescence and subsequent downward flow of the collected spray droplets. The sprays are operated continuously, except for those installed near the precipitator outlet, which are operated only periodically. These spray nozzles were not in operation during the test program. The irrigating fluid is a high pH sodium-based liquid which is returned to clarifiers and a cryolite recovery plant. Plant personnel reported that the cryolite recovery system is essentially a closed liquid loop, which results in a solids content of about 5% by weight being returned to the wet ESP - scrubber system. Liquor flow through the wet ESP during the test program was constant at 31.5 l/sec (500 gal/min), which gives a liquid to gas ratio of about 0.7 l/m^3 (5.3 gal/1000 ft^3). Liquor temperature, based on measurements reported by plant personnel, ranges from 90 to 104°F, and is usually 94 to 95°F. No significant temperature drop has been observed in the liquor loop across the precipitator.

Voltage and current readings were obtained from the panel meters of the 553 precipitator periodically during the test program. At the conclusion of the test program, voltage-current curves were obtained for the unit with the spray system operating normally. The secondary voltage-current relationships are given in Figure 21, along with the range of operation that was observed for each electrical set during the test program. The difference

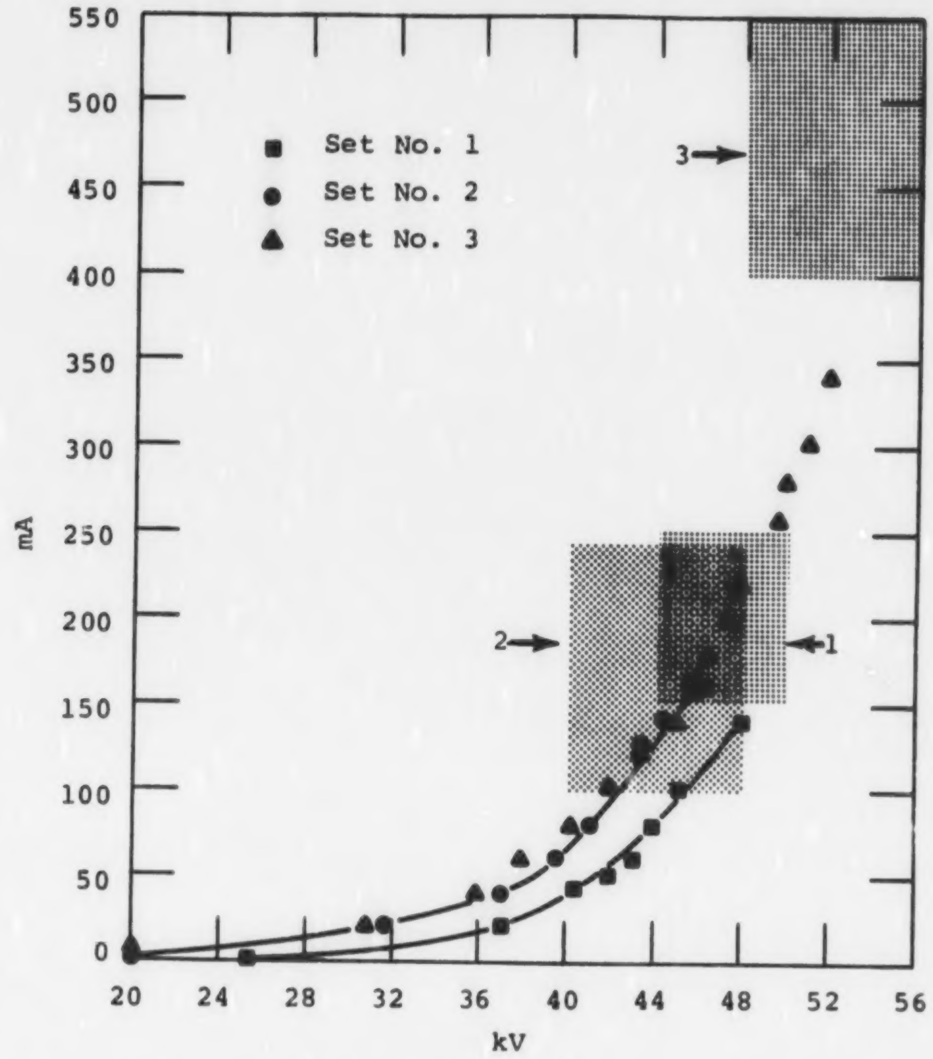


Figure 21. Voltage Current Relationship (Manual Control) and Operating Ranges (Automatic Control) Shaded Areas Designate Observed Range of Operation For Each Electrical Set During the Test Program

between the voltage-current curves and the operating ranges is a result of the fact that, in normal operation, the power supplies are operating under automatic control with a certain spark rate, whereas the V-I curves were obtained by manually increasing the applied voltage until sparking occurred. The plant personnel were operating the power supplies at a spark rate which was believed to maximize the time-averaged electric field.

The V-I curve for the first electrical set is shifted toward high voltages for a given current when compared with readings from the other electrical sets. This behavior is often observed and is a reflection of the higher space charge density contributed by the higher particulate loadings which exist in the inlet field. Although the third field operates at a relatively high current, the average current density for all three sets was only about 30 na/cm^2. The resistivity of the particulate is not a factor in the wet mode of operation.

Figure 20 presented fractional efficiencies and a predicted curve obtained from a theoretically based computer model of an electrostatic precipitator[1]. The mathematical model calculates theoretically expected collection efficiencies for representative particle diameters as a function of precipitator operating conditions. Predicted collection efficiencies for each particle diameter are a function of the electric field, the charge on the particle, and the ratio of collection area to gas volume flow rate. Fair agreement is obtained between the measured efficiencies over the particle diameter range 0.25-1.3 μm, but the measured values depart drastically from the predictions and from the trends indicated by the previously discussed laboratory measurements, at diameters larger than 1.5 μm. This apparent departure from the expected functional form may be caused by the generation of particles within the device, possibly originating from the liquid sprays or from reentrained liquid that is not captured by the outlet transverse baffles, which are considered by the manufacturer to function as an electrostatically augmented mist eliminator. It should be noted that the diameter band 0.25-1.3 μm, based on the Andersen measurements, represents 54% of the mass at the inlet and 56% of the mass at the outlet.

Electrostatic precipitator performance is often described by an empirical performance parameter termed the precipitation rate parameter. The parameter is obtained by evaluating the Deutsch equation using the overall mass efficiency and the ratio of volume flow to plate area:

$$w_p = \frac{V}{A} \ln \left(\frac{100}{100-\eta}\right)$$

Evaluation of this relationship using the data in Table 4 gives the results presented in Table 5. A predicted precipitation rate parameter may be obtained from the computer model based on the inlet size distribution obtained from the Andersen impactor measurements. Based on the predicted efficiencies indicated by Figure 20, numerical integration over the inlet size distribution gives a total predicted penetration of 1.1% (98.9% efficiency), and predicted precipitation rate parameter of 7.3 cm/sec, which shows fair agreement with the data in Table 5. Figure 20 shows, however, that the model underpredicts fine particle collection efficiencies, and overpredicts collection for particles larger than about 0.60 μm.

SUMMARIES OF TRIP REPORTS TO WET ESP MANUFACTURERS AND USERS

Dr. Charles E. Bates, head of the metallurgy section, has met with representatives of Lurgi in Frankfurt, West Germany, and British Steel Corporation in Moorgate, England. The following paragraphs summarize the more important aspects of these meetings.

Visit to British Steel Corporation

British Steel Corporation began applying wet electrostatic precipitators to electric arc furnaces about ten years ago to eliminate a fluorine problem in the effluent which, for the case of two plants, resulted in the development of fluorosis in cattle grazing nearby. Effluent particles from the electric arc furnaces are predominantly under one micron in diameter. Therefore, the only choices for emission control were electrostatic precipitators, bag filters, and venturi scrubbers. The difficulties with bag filters were that the temperatures of the gas streams were quite high, the particles quite small, and the bags would tend to plug. The presence of moisture and fluorine eliminated the use of fiberglass bags, and the operating costs of venturi scrubbers were prohibitive. After considering the possibilities, British Steel decided to install wet precipitators. Initially, the design did not permit 100% saturation of the gas before entering the precipitator, and after four years of labor and much cost, it became apparent that 100% saturation was essential at all times. This saturation must be achieved in a conditioning chamber because of the time required to fully saturate the gas stream. British Steel found that if the gas entering the precipitator were not cooled and completely saturated, the warm, moist iron oxide would stick to the baffle, wires, and plates of the precipitator like cement, but if the effluent were cooled and wet, the iron oxide would not stick. Since water carry-over during flushing caused sparkover and could possibly knock out a complete power supply, individual power supplies were installed on each stage of the precipitator to enable sections being cleaned to have the

TABLE 5

PRECIPITATION RATE PARAMETERS

Run No.	Gas Flow, m^3/sec	Mass Efficiency, %	Precipitation Rate Parameter, cm/sec
1	44.6	95.03	4.90
2	43.5	95.34	4.88
3	44.4	96.51	5.45
4	43.9	98.02	6.30

power turned off. The first installation had two fields in series, but while the plates in one section were being washed, only 50% of the cleaning capacity was being utilized. In the second installation, the arrangement was three fields, so that two fields could operate while the third was being cleaned. All three fields operate expect when washing and all precipitators are washed intermittently for 3-4 minutes during each 30 minutes of operation with high pressure water sprays. Constant irrigation proved unsatisfactory because of irregularities in either the water flow or plate shape.

The first precipitators installed by British Steel were designed based on a precipitation rate parameter of 10 to 12 cm per second. Experience showed that better results were obtained if the design precipitation rate parameters were reduced to 7 to 8 cm/sec. Specifications required by British Steel for wet precipitators recently constructed include those given in Table 6.

Several types of discharge electrodes were tested prior to installation of the electrostatic precipitators at British Steel. Collection electrodes are of the plate type. Initially a mild steel barbed wire was used, but dust bonded to the wire, leading to corrosion. This same experience occurred when a galvanized wire was used. Differently designed wires were found to be satisfactory, but the most successful design proved to be a stainless rod with stainless spikes drilled or welded into the rod's surface. The stainless steel rod gave the necessary rigidity, and the spikes provided the necessary field strength (shown in Figure 22).

The maintenance costs of these wet precipitators are now quite low and no unscheduled maintenance is experience. The operating costs consist of costs for power, water supplies, and maintenance, with about 1/3 of this cost due to maintenance. The power supplies, with automatic voltage control, are rated at 60 kV and 450 milliamps. Silicon rectifiers are employed and the primary power supply is 415 volts, 50 cycles, ± 6%. The precipitators are supplied by W. C. Holmes of Huddersfield in Yorkshire.

Visit to Lurgi Apparate - Technik GmbH, Frankfurt, Germany

Lurgi is of the opinion that wet precipitators are applicable where the gas is already wet or the resistivity of the dust is so high that water must be added to saturate the air, thus lowering resistivity. If large amounts of water must be added, or if the gas volumes are not too high, they prefer to use a scrubber and avoid some of the corrosion and maintenance problems and high capital costs associated with the wet precipitators. To capture

TABLE 6

PERFORMANCE CHARACTERISTICS OF WET PRECIPITATORS SPECIFIED BY BRITISH STEEL

Gas Flow	43 m^3/sec at 60°C
Particle Size Distribution of Inlet Dust	Particles range from 5 μm to .1 μm diameter, 95% less than 0.5 μm
Precipitation Rate Parameter	8.5 cm/sec maximum
Collection Efficiency	97.5%
Inlet Dust Loading	4.6 g/m^3 (2.0 gr/ft^3) at N.T.P. dry (maximum)
Outlet Dust Loading	0.115 g/m^3 (0.05 gr/ft^3) at N.T.P. dry (maximum)

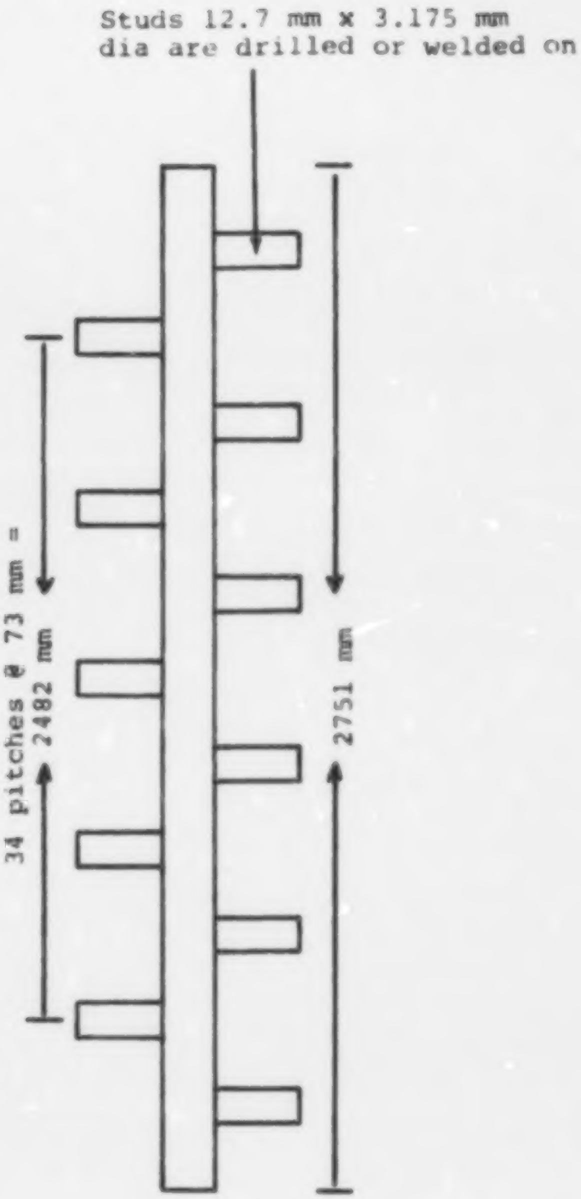

Studs 12.7 mm x 3.175 mm dia are drilled or welded on
34 pitches @ 73 mm = 2482 mm
2751 mm

Figure 22. Discharge electrodes for wet ESP units at British Steel.

particulate and gases, one could use a scrubber to remove chloride and sulfur oxides. Lurgi has never looked at wet precipitators for power plant applications because they consider them too costly and complicated. Lurgi has installed wet precipitators on cupolas, arc furnaces, basic oxygen furnaces, blast furnaces, and scarfers.

Basic Oxygen Furnaces -

Basic oxygen furnaces commonly use 40-60" pressure drop scrubbers for particulate control, but Lurgi has built about five wet electrostatic precipitators for this application. These wet cleaning plants require considerable maintenance due to the large amount of oxygen, fluorides, and sulfides in the gas, which lead to corrosion of the internal parts of the control system. Corrosion could be avoided by using stainless steel but this would be prohibitively expensive. The market for wet precipitators for this application does not appear favorable to Lurgi.

Scarfers -

Scarfers commonly use water sprays to cool the grit produced by the scarfing operation, so a wet precipitator becomes a natural choice. Saturation of the gas before entering the precipitator is essential as is maintaining an adequate flow of water over the plates to prevent buildup. Fully saturated effluent does not bond, and in fact, is easily washed off. The gas volumes are relatively low, so one can afford stainless steel internals, thereby minimizing maintenance costs. The wet precipitator provides good performance, low operating cost, and can be small in size when applied to scarfers. Lurgi has sold seven or eight wet precipitators for effluent control of scarfing operations over the past few years.

Blast Furnaces -

Electrostatic precipitators were very popular on older blast furnaces where the top pressure was not particularly high. At the present time, however, all blast furnaces being built have top pressures of 15 to 20 psi and part of this pressure is available to do work. With a high top pressure, sufficient energy is available to simply pass the gas through a venturi and allow the gas expansion to do much of the work required. Therefore, high energy wet scrubbers, using this gas energy, can be employed just as economically with a lower capital investment compared to precipitators. The wet precipitator does work well on blast furnaces and corrosion is not a problem because of the very low oxygen partial pressure, and hence, low corrosion potential, of the effluent gas. Lurgi has about 250 wet precipitators in operation and a partial list of these was furnished to Southern Research. Demand for wet precipitators for blast furnace cleaning is not expected to increase except in undeveloped countries where sophisticated furnaces will not be used.

Cupolas -

Small gas volumes are involved in cupola operations compared to most processing equipment, and wet precipitator usage is possible. Lurgi has built three or four wet precipitators and two or three dry precipitators in the last few years for foundries, but because of the small profit margin involved for supplying pollution equipment for small foundry operations, Lurgi does not expect to pursue it.

Electric Arc Furnaces -

The most common control devices for arc furnace effluents are bag houses and electrostatic precipitators. At this time Lurgi leans toward dry precipitators since the dust resistivity is reasonable when the gas is diluted with plant air and cooled to about 70°F. Above a gas volume of about 500,000 cu. meters/hr, the precipitator is less expensive than a bag house in total operating costs.

Design Details -

Lurgi wet precipitators normally use plates and two types of water supply. The continuous water sprays (about 45-50 psi) employ nozzles to achieve as fine a mist as possible, using clean water. The second system of sprays provides a high volume of water to the plates every three or four hours to give the plates a good cleansing. During this flushing operation the power is left on, but with voltage reduced to 10-15 kV instead of the normal 40 kV. The precipitator normally has three fields, sometimes four, and one field is washed at a time.

When the gas going through the precipitators is incompletely saturated, buildup and corrosion can be serious problems. Basic water will cause buildup and acid must be added to get a release. Acidic water will cause corrosion in a precipitator.

There are very few, if any, gravity water flows in use because of difficulty in maintaining uniform water flow down the plates (the weirs cannot easily be kept level and the plates or tubes cannot easily be kept straight). Precipitation rate parameter values of 7 to 10 cm/sec in wet precipitators and 3 to 5 cm/sec in dry precipitators are obtained with the same distance between wires and plates. The precipitation rate parameter in dry precipitators at 70 to 90°F using plant dilution air will sometimes run as high as 10 cm/sec, but will vary widely with dust resistivity.

On old blast furnaces, dust loads of 0.78 to 1.3 grams per cubic meter are common in the raw effluent from the furnace. A cyclone then drops the dust loading to 0.65 to 0.90 grams/m^3 With a center charge going into the blast furnace, the dust coming out is typically 0.5 to 0.65 grams/m^3. The gas is then cleaned by a wet scrubber which cleans the effluent to 30-100 mg/m^3, and then finally by a precipitator which cleans the gas to about 5 mg/m^3.

If the gas is to be sent to a turbine, the dust loading must not be higher than 0.5-1.0 mg/m^3, which can usually be achieved with a secondary precipitator. The discharge electrodes of such a precipitator are schematically illustrated in Figure 23. Commonly three fields are used. In the first field there will be 8 mm diameter stainless steel rod with welded studs spaced on the rod. The rod in the second stage is the same size but with square studs welded on it. In the third stage, a bare wire is used with water flowing over it, the water stream itself providing enough asperities to cause corona for charging the dust.

Mikropul Division of United States Filter Corporation

Mikropul has recently constructed large-scale wet precipitators on aluminum pot lines, and the company has also been actively pursuing wet precipitator usage in other application areas. During the course of this contract, a trip was made to the Mikropul Plant in Summit, New Jersey, and discussions were held concerning Mikropul's experience and pilot plant test program.

At the time of the plant trip, the company was running pilot plant tests of a wet precipitator designed for collection of sulfur oxides and fly ash from a coal-fired power plant. The pilot plant is equipped with a propane burner to produce synthetic flue gas. Collected fly ash from a coal-fired boiler is injected with a blower, and SO_2 is added from a gas cylinder. At the time the visit was made, SO_2 and particulate removal trails were being performed with a calcium-based process. Liquid to gas ratios were said to be of the order of 100 gal/1000 ft^3, and SO_2 removal efficiencies as a function of liquid to gas ratio were reportedly typical of data reported by other investigators. Scaling caused by precipitation of calcium salts on the electrodes was viewed as the major problem area to be overcome for power plant applications.

Mikropul's objective is to produce a single "box" for removing both SO_2 and particulate. The pilot plant design essentially consists of a scrubber, a particle precharger, a discharge electrode and parallel plate collector, followed by an electrostatic demister section which can be periodically washed. In addition to the calcium-based process, a sodium-based process

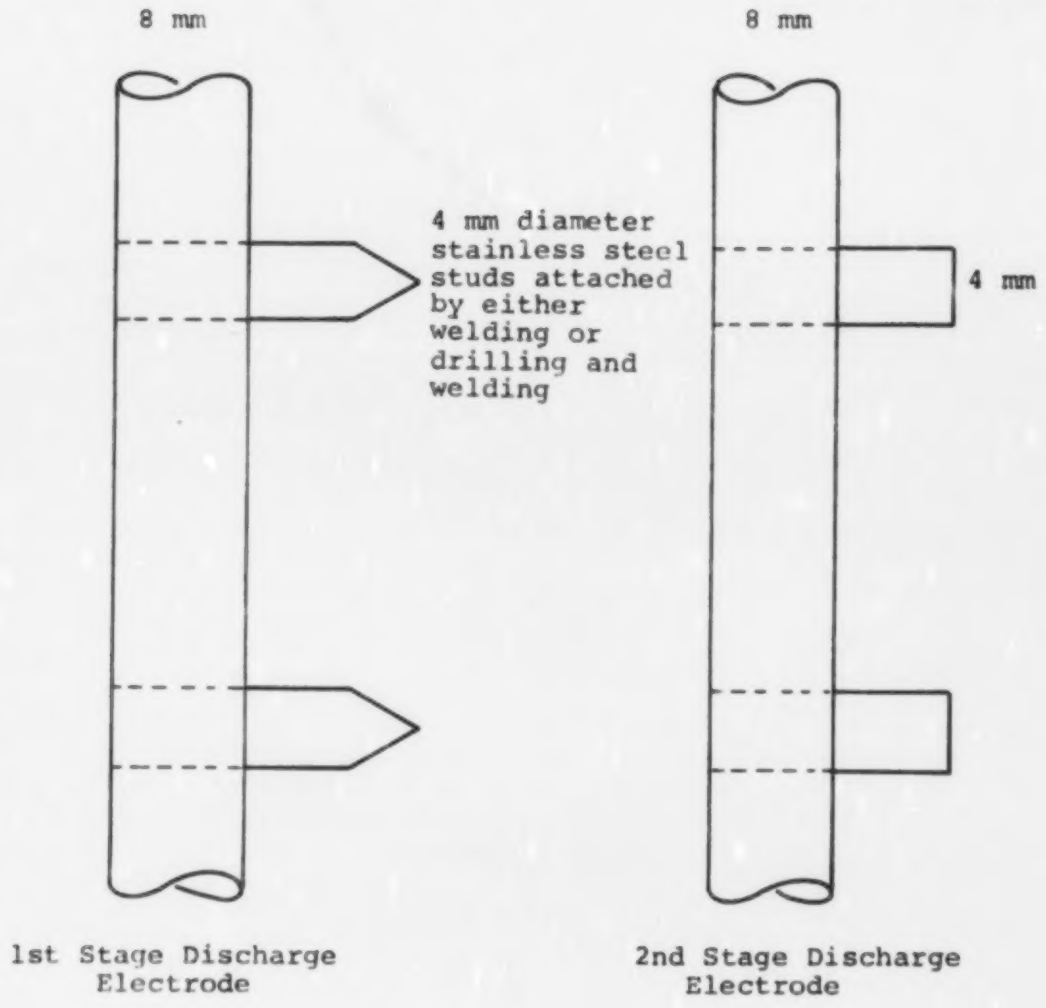

8 mm
8 mm
4 mm diameter stainless steel studs attached by either welding or drilling and welding
4 mm
1st Stage Discharge Electrode
2nd Stage Discharge Electrode

Figure 23. Lurgi Discharge Electrodes

is also under consideration for use with the wet precipitator system.

Mikropul reported that they have obtained pilot plant data from the following application areas:

Tire-cord curing ovens
Glass melting furnaces
Fiberglass forming lines - curing ovens, cooling section
Coke ovens
Sinter plant
Anode baking furnaces
Secondary brass melting furnaces
Phosphorus reduction furnace
Borax dust.

Table 7 gives a list, furnished by Mikropul, of their wet precipitator installations.

Research Cottrell

A telephone conversation held with a staff member of Research Cottrell concerning their current interests in the wet precipitator market. He reported that his company has no recently constructed wet precipitator installations. Most of their wet units have been used on blast furnaces, and many of these are being replaced by high energy scrubbers.

Western Precipitator Division of Joy Manufacturing Company

Discussions were held with representatives of Western to determine their opinions concerning the future application of wet precipitators. Western manufactures wire-pipe wet ESP's, typically with 96 ten-inch diameter, 15 ft long pipes in each module. These modules have recently been used on scarfing machines, with each unit treating about 25,000 cfm. No test data was available for these units.

Although Western has considered the use of wire-pipe wet ESP's for incorporation into an SO_2 removal system, they do not consider it practical, because of corrosion and resultant high materials cost, to use a wet ESP as the primary particle remover. In trials of a scrubber-wet precipitator system that have been conducted by Western, the wet ESP was said to function as a mist eliminator following a low energy scrubber. Western recommends "hot" precipitators for particulate collecting in coal-fired power plants.

Blast Furnace Wet Precipitator Installation

A visit was made to a steel mill which uses wire and tube-type

TABLE 7

MIKROPUL WET ELECTROSTATIC PRECIPITATOR INSTALLATIONS

Location	Description	Capacity, cfm	Installation Date
Aluminum Potlines			
Martin Marietta Goldendale, Wash.	20 units	7,500 cfm	1971
Martin Marietta The Dalles, Oregon	7 units 4 units	12,000 cfm 6,000 cfm	1972
Reynolds Metals Co. Longview, Wash.	pilot unit	50,000 cfm	Oct. 1971
Phase I	1 unit 4 units	50,000 cfm 100,000 cfm	June 1973
Phase II	4 units 12 units	50,000 cfm 100,000 cfm	
Phase III	10 units	100,000 cfm	1974
Fiberglas Forming Lines			
Certain-Teed Prod. Kansas City, Kansas	2 units	100,000 cfm	1973
Carbon Anode Baking Furnace			
Airco Speer Carbon Graphite Niagara Falls, N.Y.	4 units	9,000 cfm	1973
Reynolds Metals Co.	1 unit	26,500 cfm	1973
Oil Mist			
General Motors Corp. Buick Division Flint, Michigan	1 unit	15,000 cfm	1972
Sodium Sulfite Mist			
Shattuck Chemical Co. Denver, Colorado	1 unit	3,500 cfm	1972
Phosphorus Rock Dust			
W.R. Grace & Co. Bartow, Florida	2 units	115,000 cfm	1974
Coke Oven Emissions			
Dominion Foundry & Steel Hamilton, Ontario	2 units	150,000 cfm	1974-1975

wet precipitators for cleaning blast furnace gas. Two precipitators are employed, each of which has two units. Each unit consists of 126 pipes 8 in. in diameter and 15 ft long, giving a total of 504 tubes with a collecting area of 15833 ft^2. These units were installed in the 1941-1942 time period on a large blast furnace. They are now being used on a smaller blast furnace, and a high energy venturi has replaced the wet precipitators on the large blast furnace. The current plan is to phase out the precipitators in about two years, and use high energy scrubbers exclusively.

Performance tests on the wet precipitators were conducted by Research Cottrell in April of 1960, and Table 8 gives the data reported to the user. At the time these tests were conducted, the units were powered by mechanical rectifiers. These have since been replaced with two tube-type rectifiers, each of which powers one precipitator. During our visit, the panel meters indicated a total DC current of 0.5 amps, which would result in an average current density of about 30 $\mu a/ft^2$. The precipitators are preceded by wet scrubbers which cool the furnace gas and remove the relatively large particles. The gas flow and efficiency data in Table 8 result in precipitation rate parameters between 9.5 and 11.5 cm/sec. These values are approximately within the range of design values reported by Oglesby and Nichols[4] for blast furnace wet precipitators.

Although the management at the blast furnace wet ESP installation that we visited was planning to phase out the units, their performance was said in general to be satisfactory. The tubes require cleaning once or twice a year, and the precipitators have been retubed at least once since their original installation. The general reasoning seemed to be that operating a blast furnace at relatively high pressure was advantageous, and this pressure could be effectively utilized in a scrubber for particulate removal.

TABLE 8

TEST RESULTS OBTAINED BY RESEARCH COTTRELL ON A BLAST FURNACE WET PRECIPITATOR INSTALLATION

Test No.	*1	*2	*3	**4	**5
Date	4/22/60	4/25/60	4/25/60	4/26/60	4/26/60
Furnace Wind, cfm	73,000	71,000	71,000	64,000	64,000
Blast Pressure, psig	24.0	22.0	22.0	19.0	18.5
Top Gas Pressure, "H_2O	40	40	30	43	44
Hot Blast Temperature, °F	1050	1050	1050	950	890
Precipitator Inlet Gas Temp.,°F	88	90	90	90	90
Gas Volume, cfm	99,000	103,500	103,500	86,000	86,000
Precipitator Rating, %	90	94	94	156	156
Dust Concentrations, Grains per cu. ft. Dry Gas @ 60°F & 30" Hg.					
Inlet	0.133	0.0915	0.128	0.0675	0.0698
Outlet	***	0.0051	0.00705	0.00861	0.0103
Precipitator Efficiency, %	***	94.4	95.0	87.2	85.3

*Tests made with gas from No. 2 Furnace passing through both precipitators.

**Tests made with gas from No. 2 Furnace passing through one precipitator.

***Contaminated outlet sample was discarded.

SECTION V
ANALYSIS OF POTENTIAL WET ESP APPLICATIONS

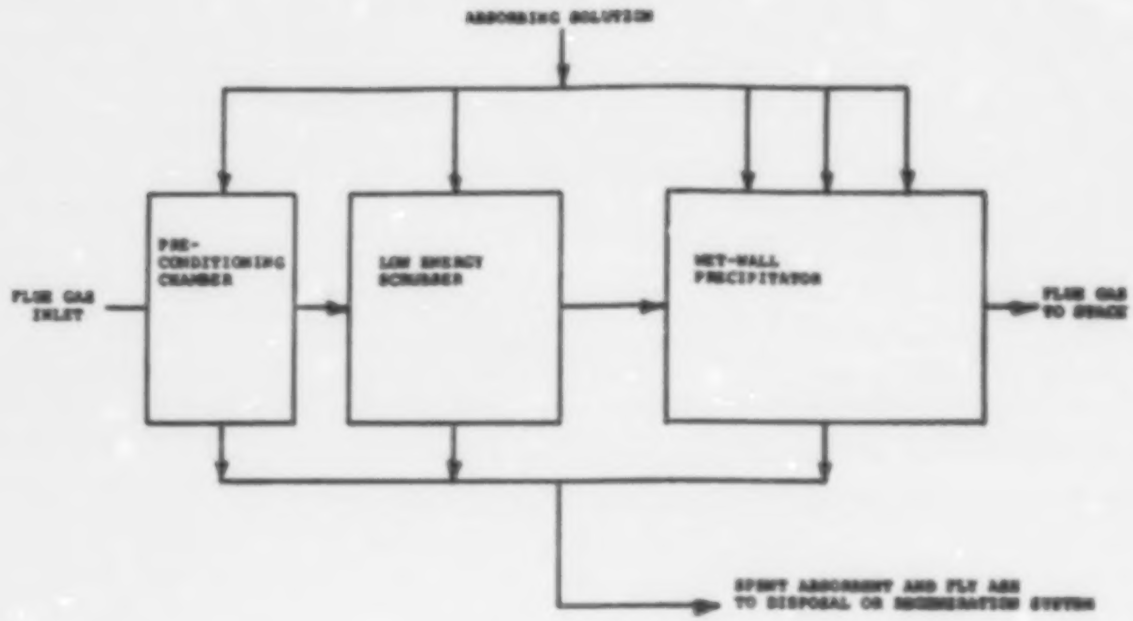
SIMULTANEOUS REMOVAL OF PARTICULATE AND SULFUR OXIDES

The recent emphasis on reduction of sulfur oxide emissions has resulted in a number of processes which involve wet scrubbing of flue gas to remove both particulate and sulfur oxides. High efficiency particulate removal in scrubbers generally requires pressure drops of 25 to 50 cm of water or more, which for utility power plants involves a considerable energy loss. The removal of sulfur oxides, however, can be accomplished with less energy in a scrubber which is designed primarily for gas absorption. The electrostatic precipitation process can collect particulate with less energy expenditure than with wet scrubbers, but the sensitivity of dry precipitators to fuel composition changes and resultant dust resistivity variations is a serious drawback. It is therefore of interest to consider the use of a wet precipitator, which is not sensitive to dust resistivity, as the primary particulate collection device for small particle removal.

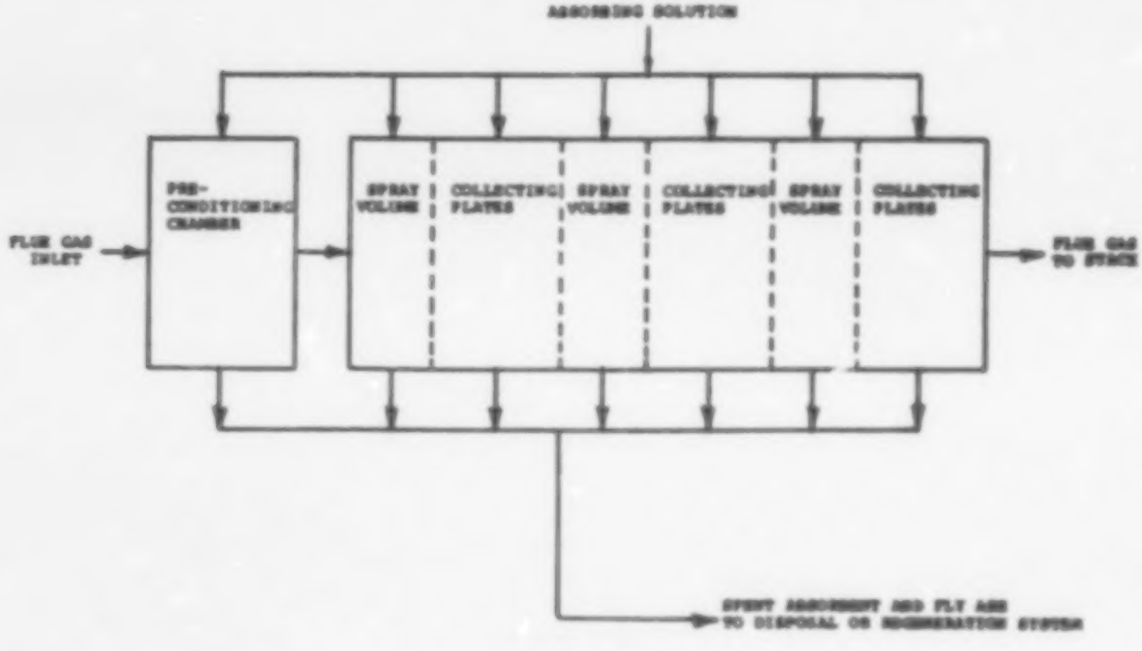
Figure 24 illustrates possible configurations of a combination scrubber-wet precipitator. As indicated in the illustration, the device may consist of a separate low energy scrubber and wet-wall precipitator, or the scrubber and precipitator can be combined into one unit with alternating scrubbing and collecting plate sections. In either arrangement, it is obvious that simultaneous particulate collection and gas absorption will occur in the precipitator sections. Consideration will therefore be given to the potential mechanisms of sulfur oxide removal which exist in the electrical sections. These mechanisms are:

1. Migration of ionized SO_2 molecules to the collecting electrode under the influence of an electric field.
2. Diffusion and absorption of SO_2 into a basic solution irrigating the collecting electrodes.
3. Absorption of SO_2 by droplets of basic solution which may be sprayed into the interelectrode region.

An estimation of the maximum amount of SO_2 which might be removed by electrical transport can be calculated by assuming a current density and a plate area to volume flow ratio (specific collecting area). As an example, we will consider a wet precipitator with a specific collecting area of 59.1 $m^2/(m^3/sec)$ (300 $ft^2/1000$ cfm), which operates with a current density of 100 nA/cm^2. The corona


ABSORBING SOLUTION
PRE-CONDITIONING CHAMBER
LOW ENERGY SCRUBBER
WET-WALL PRECIPITATOR
FLUE GAS INLET
FLUE GAS TO STACK
SPENT ABSORBENT AND FLY ASH TO DISPOSAL OR REGENERATION SYSTEM

OPTION A


ABSORBING SOLUTION
PRE-CONDITIONING CHAMBER
SPRAY VOLUME
COLLECTING PLATES
SPRAY VOLUME
COLLECTING PLATES
SPRAY VOLUME
COLLECTING PLATES
FLUE GAS INLET
FLUE GAS TO STACK
SPENT ABSORBENT AND FLY ASH TO DISPOSAL OR REGENERATION SYSTEM

OPTION B

Figure 24. Schematic Diagram of Scrubber-Wet Precipitator System.

current density is given by

$$100 \times 10^{-9} \frac{\text{amp}}{\text{cm}^2} \times 10^{4} \frac{\text{cm}^2}{\text{m}^2} \times 1 \frac{\text{coul}}{\text{amp-sec}} = 10^{-3} \frac{\text{coul}}{\text{m}^2\text{-sec}}$$

If we assume that the current is carried by singly charged ionized gas molecules, the rate at which such molecules are transported to the collecting electrode is

$$10^{-3} \frac{\text{coul}}{\text{m}^2\text{-sec}} \times \frac{1 \text{ ion}}{1.6 \times 10^{-19} \text{coul}} = \frac{6.25 \times 10^{15} \text{ ions}}{\text{m}^2\text{-sec}}$$

From the specific collecting area and the removal rate of ions, it can be seen that the number of ions removed per cubic meter of gas is given by

$$\frac{6.25 \times 10^{15} \text{ions}}{\text{m}^2\text{-sec}} \times \frac{59.1 \text{ m}^2}{\text{m}^3/\text{sec}} = 3.69 \times 10^{17} \frac{\text{ions}}{\text{m}^3}$$

At 120°F, it can be shown that the number of gas molecules in a cubic meter of gas is equal to 2.28×10^{25}. Thus, the fraction of the total number of gas molecules which could be electrically transported to the collecting electrodes is equal to

$$\frac{3.69 \times 10^{17} \text{ ions/m}^3}{2.28 \times 10^{25} \text{ molecules/m}^3} = 1.62 \times 10^{-8}, \text{ or } 0.0162 \text{ ppm}$$

It is therefore apparent that the corona current cannot be expected to directly contribute significantly to the amount of sulfur oxides which might be removed in a wet precipitator.

The second potential mechanism is absorption of SO_2 into a basic solution irrigating the collection electrode as a result of the reduced partial pressure of SO_2 above such a solution. An estimate of the gas phase mass transfer coefficient applicable to these conditions may be obtained from the Sherwood equation,[5] which was obtained for wetted wall columns with the fluid descending in laminar flow and the gas ascending in well developed turbulent flow. The equation is

$$\frac{K_g d}{D_m} = 0.023 \left(\frac{du\rho}{\mu}\right)^{0.83} \left(\frac{\mu}{\rho D_v}\right)^{0.33}$$

where

d = equivalent diameter of gas passage
D_m, D_v = molal and volumetric diffusivity of gas being absorbed (SO_2)
u = gas velocity
ρ = density of gas phase
μ = viscosity of gas phase
K_g = gas film coefficient

For a precipitator with 25.4 cm plate spacing and a gas velocity of 1.52 m/sec (5 ft/sec), the above correlation gives K_g as 0.183 g mole/[m^2 (sec) (mole frac.)]. If we make the assumptions that the gas phase resistance is the rate controlling step and that the partial pressure of SO_2 above the solution is negligible, the absorption rate may be estimated from

$$N = K_g(A)\ (y_{ln})$$

where

N = moles/sec of SO_2 removed
A = absorption area
y_{ln} = log mean mole fraction of SO_2 in gas phase
$= (y_{in} - y_{out})/\ln \left(\frac{y_{in}}{y_{out}}\right)$

For the previous calculation of the amount of SO_2 which could be electrically transported, we assumed an A/V ratio of 59.1 $m^2/(m^3/sec)$. If we further assume a log mean SO_2 concentration of 1000 ppm, the SO_2 removal rate for 59.1 m^2 is given by

$$N = 0.183 \frac{\text{gmole}}{(\text{m}^2)(\text{sec})(\text{mole frac.})} \times 59.1 \text{ m}^2 \times 1 \times 10^{-3} \text{ mole frac.}$$

$$= 0.0108 \text{ gmole/sec}$$

The total gas flow passing each 59.1 m^2 of plate area is 1 m^3/sec, or 37.9 gmoles/sec at 120°F. The quantity of SO_2 removed, expressed as a fraction of the total gas, is therefore

$$\frac{0.0108 \text{ gmole } (SO_2)/\text{sec}}{37.9 \text{ gmole (gas)/sec}} = 285 \times 10^{-6}$$

These calculations indicate that the solution irrigating the walls will provide sufficient interfacial area for only a minor portion of the required SO_2 removal, although it is possible that turbulence created by the electric wind in the interelectrode space may increase the value of K_g to some extent. The principal SO_2 removal, however, must be accomplished by sprays in order to increase the interfacial areas.

The use of a wet ESP in an SOx-particulate removal system must therefore be decided upon the basis of the WESP's performance as a particulate collection device. Figures 25 and 26 give computed projection of particulate collection performance of a WESP on a typical power station fly ash. These projections were obtained from the SRI-EPA precipitator computer model,[6] and the voltage-current relationships are based upon the data contained in Figure 21. A gas velocity distribution with a standard deviation of 25% of the mean velocity was used in the model for both sets of indicated electrical conditions. Gas by-passage was assumed to be 5% over two and three stages. Figure 25 indicates the expected collection efficiency relationship using what we consider to be optimistic electrical operating conditions, whereas the efficiency relationships in Figure 26 are based upon the average electrical conditions which were obtained during the test program described in Section IV. These projections suggest that a specific collecting area of 39.37 $m^2/(m^3/sec)$, or 200 $ft^2/1000$ cfm, would constitute a conservative estimate of the collection area required for achieving 99.6% or better collection efficiency of particulate.

Although in principal SO_2 removal can be accomplished by introduction of spray droplets in the interelectrode region, it is our

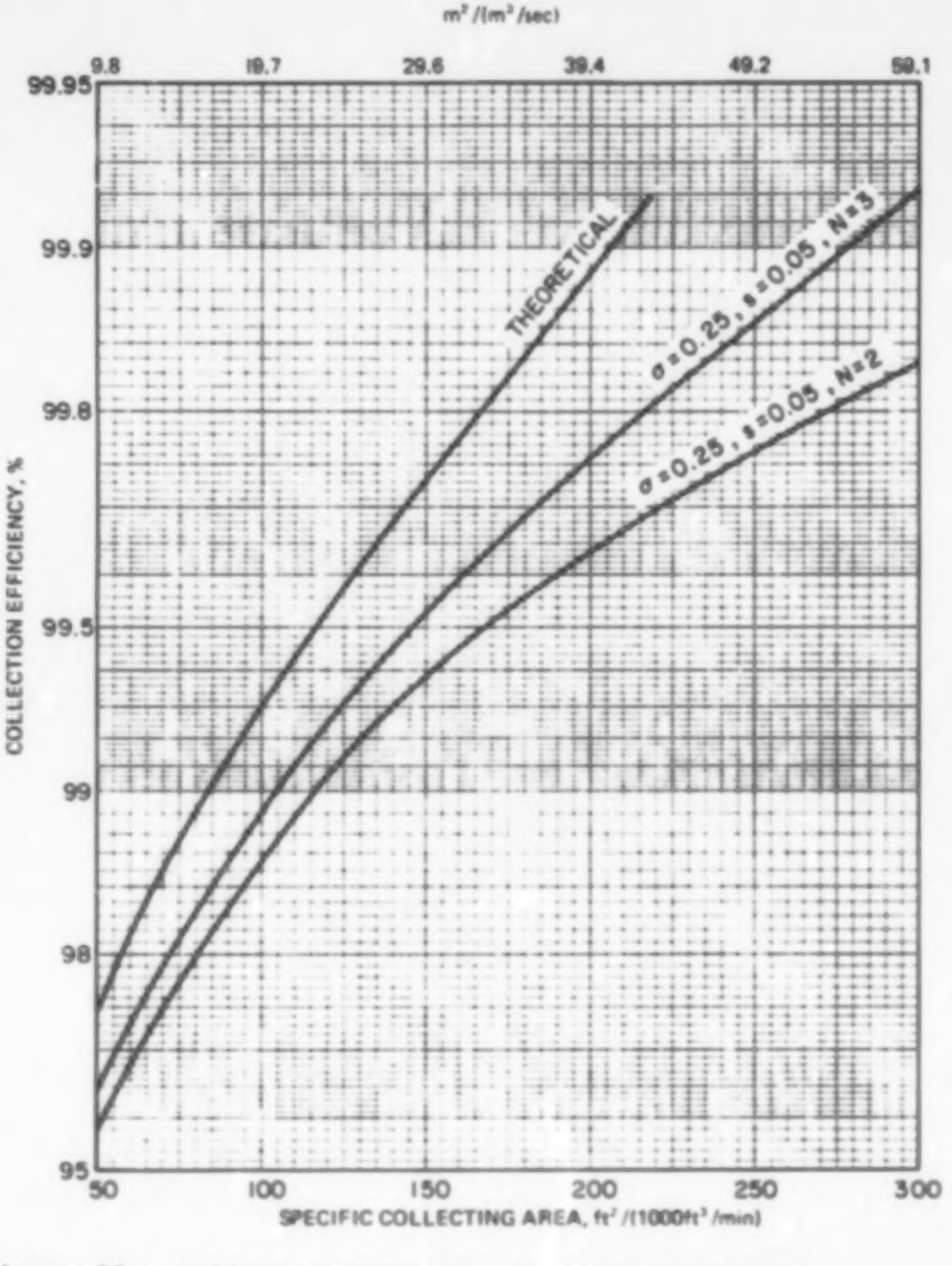


Figure 25. Collection Efficiencies Calculated With Computer Model for 50 x 10^{-9} amps/cm^2 and 50 KV

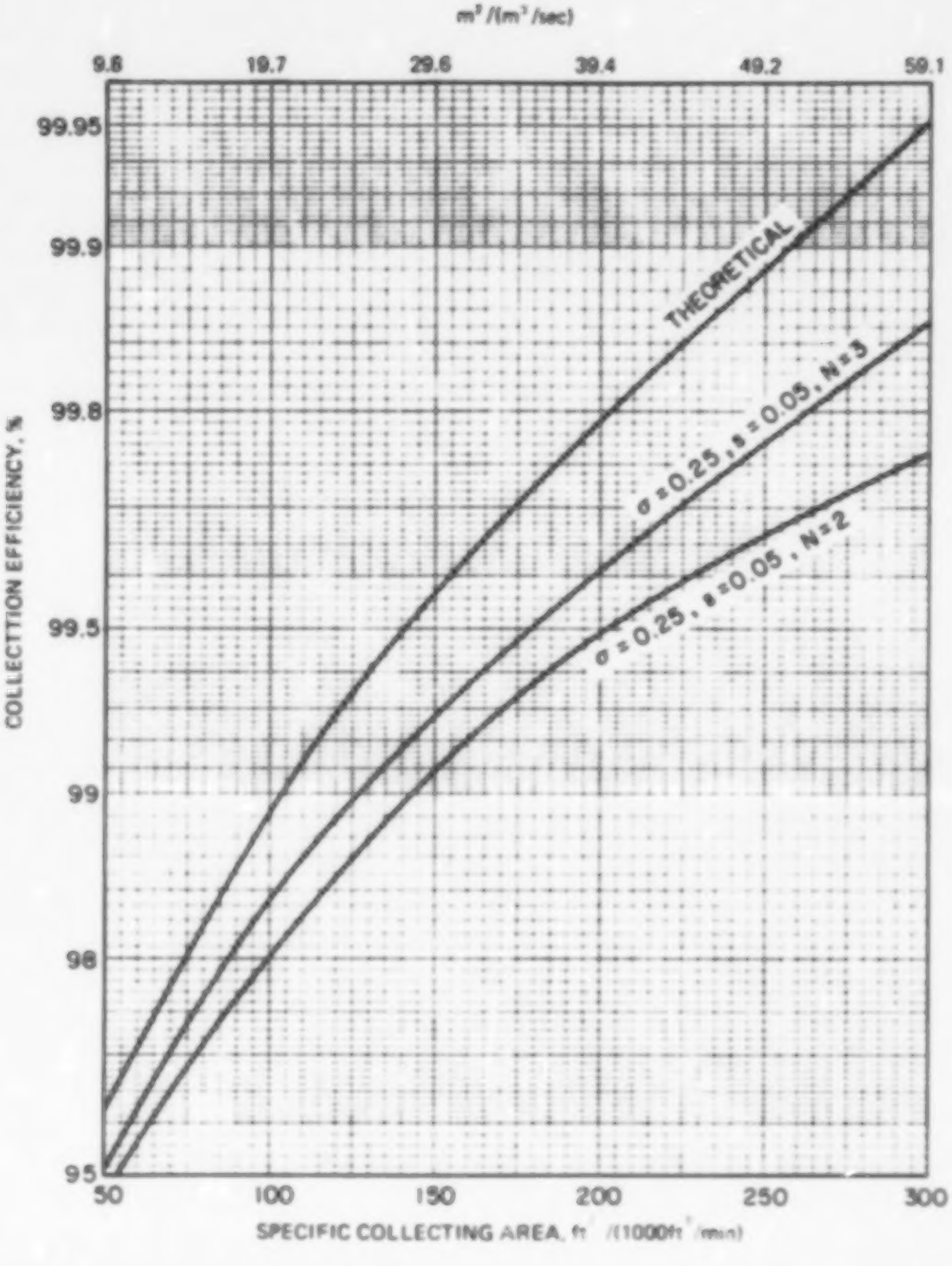


Figure 26. Collection Efficiencies Calculated With Computer Model for 33 x 10^{-9} amps/cm^2 and 47.3 KV

opinion that introduction of the sprays into the electrified region in the required L/G ratios would limit electrical operating conditions for full-scale units with practical values of plate area for each T-R set. Therefore, SO_2 removal should be accomplished in a relatively inexpensive spray tower preceding a wet ESP. Perhaps the most favorable circumstances for use of a WESP would be in a sodium-based absorption system in which SO_2 removal can be accomplished with moderate L/G ratios.

Table 9 gives a comparison of power requirements for two particulate control methods in an SOx-particulate removal gas cleaning system. Scrubber operating assumptions are based on data obtained at the EPA Alkali Scrubbing Test Facility.[7] Based on the indicated assumptions, the WESP system has lower power requirements, primarily as a result of the low pressure drop through the system. Table 10 and 11 give capital and operating cost estimates. The WESP capital costs are based on the assumption of stainless steel construction with installed costs of $\$377/m^2$, or $\$35/ft^2$, and a specific collecting area of $39.37\ m^2/(m^3/sec)$. These comparisons indicate that the WESP costs for particulate removal are about two times as great as the scrubber due to the high capital costs. The wet ESP system costs would have to be reduced by about 60% in order to have the same annual operating costs as the TCA scrubber system. Maintenance costs have not been considered quantitatively in this analysis, but the possibility of scale formation on the electrodes in the WESP is potentially a much more serious problem for the WESP than is scale formation in a scrubber vessel.

Another consideration which is not reflected in these comparisons is the performance of a dry ESP. Collection efficiencies of dry ESP's under favorable operating conditions with high sulfur coals have been measured as 99.7% with specific collecting areas less than $49.2\ m^2/(m^3/sec)$, or $250\ ft^2/1000$ cfm. Therefore, unless WESP's can be demonstrated to achieve 99.5% or better collection efficiency with SCA's considerably less than $39.4\ m^2/(m^3/sec)$, or $200\ ft^2/1000$ cfm, there is no economic justification for substituting a WESP for a conventional dry electrostatic precipitator in an SOx-particulate removal system with flue gas produced from high sulfur coals. For such instances, an economic analysis should be conducted which compares the operating costs of a scrubber-only system with those of a system consisting of a low energy scrubber and a dry ESP.

COLLECTION OF HIGH RESISTIVITY DUST

Utilities in some parts of the United States are faced with requirements for SOx removal from flue gas in which the dust resistivity is sufficiently high to limit the electrical operating conditions in the precipitator. Under these conditions, the plate area required for 99.5% or greater particulate collection

TABLE 9

POWER REQUIREMENT COMPARISON FOR PARTICULATE CONTROL IN SOx REMOVAL SYSTEMS

Item	kw/kacfm Scrubber-Wet ESP	kw/kacfm Scrubber Only (TCA)
Pump	1.080	2.03
Fan	0.468	2.30
Power for TR Sets	0.405	
Insulator Power	0.180	
Total	2.133	4.33

Assumptions:

1. Fan and pump efficiency 50%.
2. 5.08 cm H_2O ΔP in gas for scrubber-WESP system.
3. Fluid head for pumping calc. = 28.1 m.
4. L/G for scrubber-wet ESP System
   Scrubber (spray tower) = 3.4 ℓ/m^3 (25.8 gal/1000 ft^3)
   WESP = 0.7 ℓ/m^3 (5 gal/1000 ft^3)
5. L/G for scrubber only system = 7.8 ℓ/m^3 (58.2 gal/1000 ft^3).
6. 24.9 cm H_2O ΔP in gas for scrubber-only system.
7. WESP has SCA of 39.37 $m^2/(m^3/sec)$.
8. TCA particulate collection efficiency = 99.8%.
9. WESP particulate collection efficiency = 99.75%.
10. SO_2 removal = 90%.

TABLE 10

CAPITAL COST ESTIMATES FOR PARTICULATE CONTROL IN PARTICULATE-SOx REMOVAL SYSTEM

	150 MW Boiler, 183 m^3/sec (394,000 acfm) at 50°C	
Item (a)	Scrubber-WESP	Scrubber Only (TCA)
Wet ESP	2,760,000	
Spray Scrubber	105,000[10]	85,000 (c)
TCA Vessel		608,000[9]
Scrubber Fans & Motors		255,000
Total	2,865,000 (b)	948,000 (b)

(a) Elements common to both systems not included.

(b) Cost scaled to February 1975 dollars with chemical plant cost index.

(c) Presaturator.

TABLE 11

OPERATING COST ESTIMATES FOR PARTICULATE CONTROL IN PARTICULATE-SOx REMOVAL SYSTEM, $/yr

Item (a)	Scrubber WESP	Scrubber Only
Cap charges at 15%/yr	$430,000	$142,200
Energy cost (b)	40,300	81,900
	$470,300	$224,100

(a) Elements common to both systems not included.

(b) Based on 6000 hr/yr $0.008/kwh

efficiency can be 98.4 $m^2/(m^3/sec)$, [500 $ft^2/1000$ cfm], or greater if a conventional ESP is used at operating temperature in the 150°C range. The use of a WESP could lower the plate area requirements by a factor of two or more, but presently available information indicates that the increased materials costs required by wet operation would partially or completely offset the cost savings resulting from plate area reduction. The possibility of electrode scaling in WESP operation is a factor which would require pilot plant trials for an adequate evaluation.

COLLECTION OF MISTS FROM SCRUBBER SYSTEMS

The laboratory studies described in Section III indicate that the mathematical model should provide a basis for evaluating the potential effectiveness of WESP's for collecting mists from scrubber systems if a size distribution of the mist is available. Table 12 gives a size distribution, provided by EPA, of droplets at a spray scrubber exit.[8] The total droplet concentration is 11000 grams of liquid per cubic meter of gas, which is equivalent to about 80 gal/1000 ft^3. This extremely high concentration of large droplets causes two problems in using the model to project overall mass collection performance:

1. The model is based on the Deutsch equation for individual particle sizes, and the Deutsch collection mechanism does not apply to large particles (7-10 μm diam.).

2. The high droplet concentration results in high values of particulate space charge, and the effects of this space charge are not adequately represented in the model.

In view of these difficulties, results obtained from the model with this size distribution should be considered as only very rough approximations. Figure 27 shows overall collection efficiency projected by the model with the size distribution of Table 12. Wire-plate geometry was assumed, with a current density of 33×10^{-9} $amps/cm^2$ and an applied voltage of 47.3 kv. Model correction parameters for the overall mass efficiency were:

1. A gas velocity distribution with a standard deviation of 25% of the mean.

2. Gas by-passage assumed to be equivalent to 5% over two stages.

Figure 28 shows the theoretical collection efficiencies for the same current density and applied voltage, but with space charge effects due to large droplets ignored, as a function of particle diameter.

TABLE 12

SIZE DISTRIBUTION OF DROPLETS AT A SPRAY SCRUBBER EXIT

Average Droplet Diameter, cm	Cumulative Mass Loading, grams/m³
1.5	1.6
2.6	8.8
6.6	26
18	590
36	1,400
100	11,000

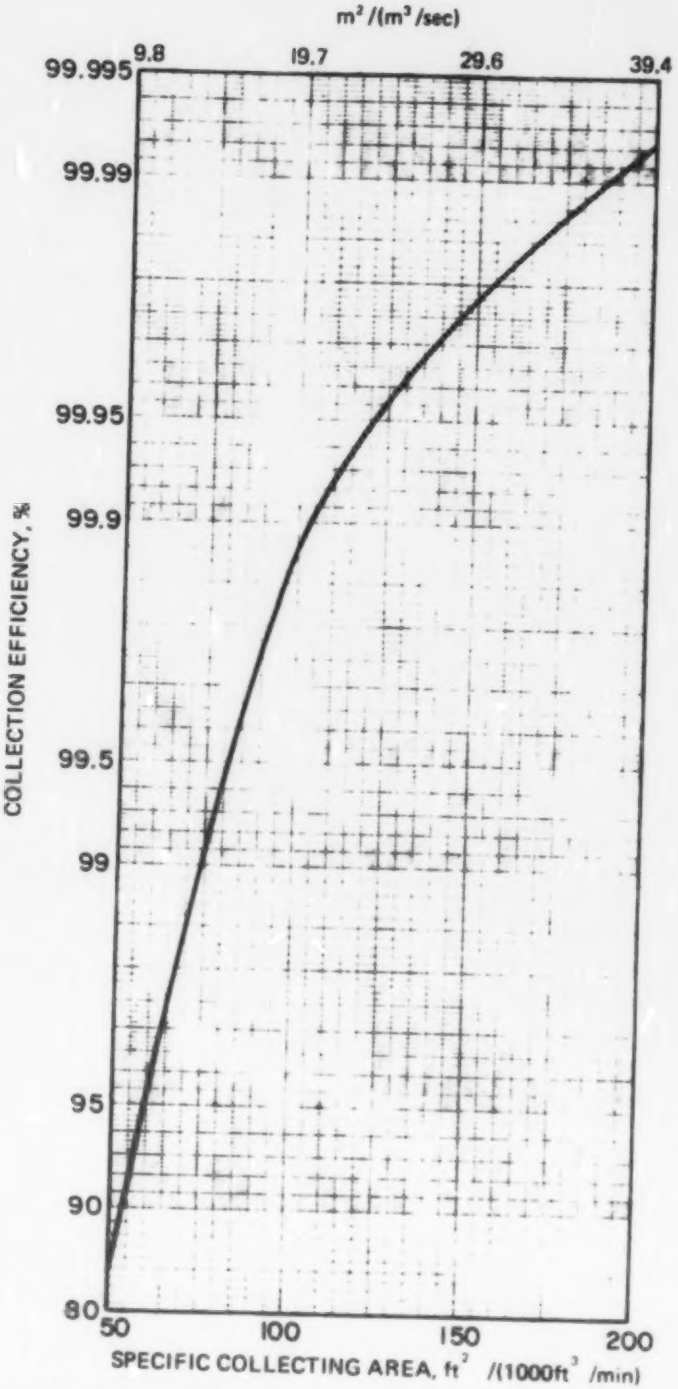


Figure 27. Collection Efficiency Calculated With Droplet Size Distribution for 33 x 10^{-9} amps/cm², 47.3 KV

$\sigma = 0.25$, $S = 0.05$, $N = 2$

These results indicate that a WESP would require about 39.4 m^2/(m^3/sec) to achieve a theoretical collection efficiency of about 99.5% on 2.5 μm diameter particles (again ignoring space charge due to the large drops), even though the overall mass collection efficiency at this SCA is projected to exceed 99.99%. If the large droplet space charge is allowed to retard collection efficiency using an approximate method for reducing free ion densities, the theoretical collection efficiencies at 39.4 m^2/(m^3/sec) for the droplet size bands are reduced as shown in Figure 28. The overall mass collection efficiency of 99.992% indicated in Figure 27 would result in an outlet mass loading of 0.88 grams/m^3, which would reduce to ∿0.09 grams/m^3 if 10% of the droplets consisted of nonvolatile solids. Thus, the model projections indicate that a WESP would require an excessive plate area to collect the distribution given in Table 12 with an efficiency such that the outlet loading from the WESP would be less than .0458 g/m^3 (.02 gr/acf). This is a result of the excessive inlet loading of 11,000 grams/m^3.

For other size distributions, it is recommended that the theoretical fractional efficiencies curves of Figure 28 be used to obtain an estimate of overall collection efficiency. These curves are based on wire-plate geometry and are valid only if particulate space charge is not sufficient to disrupt the electrical conditions. EPA is currently supporting studies to better define conditions under which space charge suppression of corona current will occur.

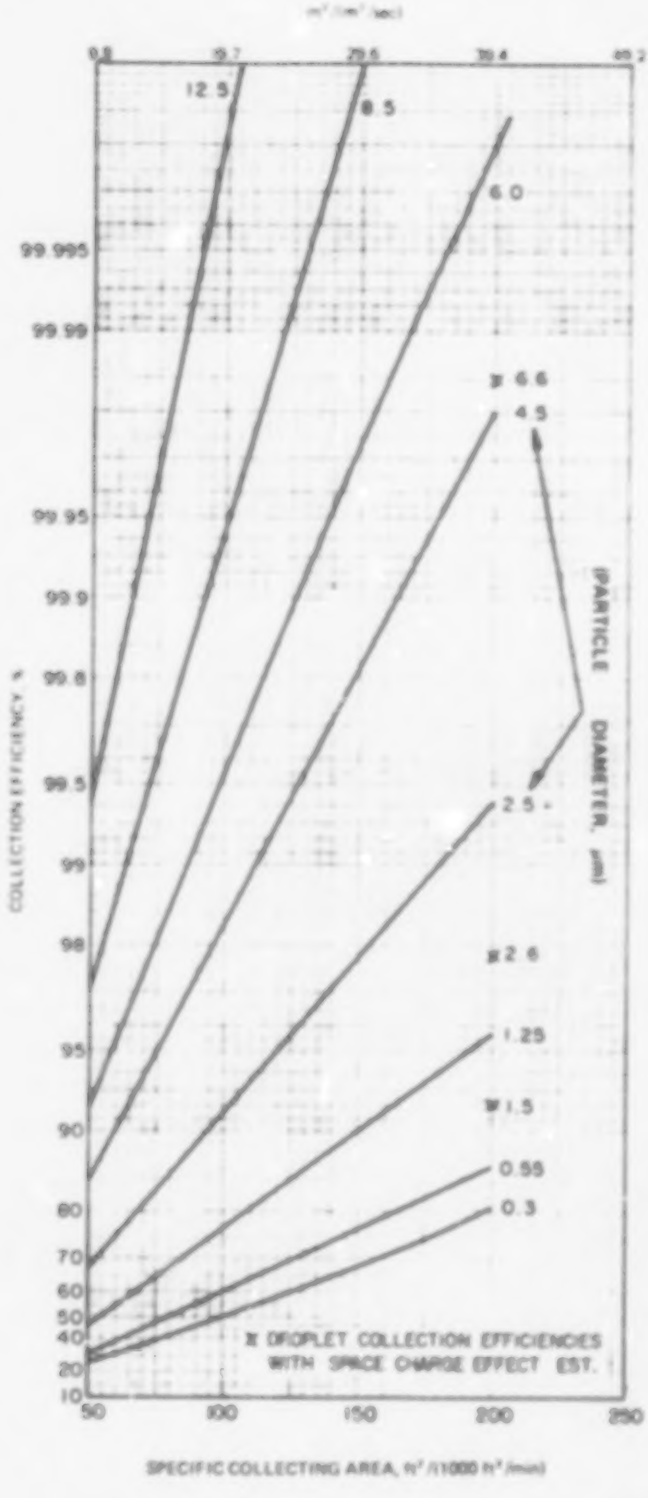


Figure 28. Theoretical Collection Efficiencies as a Function of Particle Diameter

SECTION VI
RECOMMENDED RESEARCH AND DEVELOPMENT

The laboratory studies conducted under this contract have shown that wet electrostatic precipitators can be effective collectors of fine particulate under idealized conditions. The effectiveness of WESP's used under field conditions is below the potential performance due to (1) space charge effects, which limit allowable current density, caused by incoming particulate and the electrode irrigation system, (2) deposits forming on the electrodes which cause sparkover at low applied voltage levels, (3) corrosion problems peculiar to the application area and the chosen materials of construction. Recommended research and development programs for these problem areas are given below.

PROBLEM	SUGGESTED EFFORT
1. Space charge limitation of current	a) Develop more accurate methods of calculating the effects of space on collection efficiency.
	b) Conduct laboratory studies to better define conditions under which corona quenching will occur when high concentrations of fine particulate are present.
	c) Use theoretical calculations and available data, and attempt to determine relationship between collection efficiency and sectionalization under space charge conditions. Also investigate effect of electrode geometry. Objective is to optimize fine particulate collection.

Total Effort — 2.0 man-years

2. Deposit formation

a) Survey types of electrode irrigation systems used by different manufacturers in each application area.

b) Determine location and nature of deposit formation problems.

c) Develop recommendations for implementing electrode irrigation in major application areas.

Total Effort - 1.5 man-years

3. Corrosion

a) Survey corrosion problems in each application area.

b) Establish causes of corrosion and recommend materials of construction for the various existing and potential applications.

Total Effort - 1.0 man-year

With regard to the possible use of a WESP in an SO_x-particulate removal system, the previous section has shown that, with existing WESP technology, a scrubber system appears to be more economical than a WESP-scrubber combination. In view of the potential energy saving associated with the use of the electrostatic precipitation process in the collection of particulate, there is some justification for exploring means of reducing the capital cost of a WESP for power plant applications. At present, a WESP appears to have potential value for such an application only when SO_x removal must be accomplished in the presence of high resistivity dust which results in excessive dry ESP plate areas. The following research and development efforts are suggested.

1) Determine which SO_x removal systems are feasible for use in power plants burning relatively low S Western coals (0.5 man-year).

2) Determine whether the candidate processes have the capability of providing a liquor stream which is likely to be suitable for plate irrigation (0.5 man-year).

3) If the above item gives a positive result, design a pilot-plant WESP test program for the power plant application to examine the scaling problem and to study performance under various conditions (0.25 man-year). The pilot program would also explore means of reducing materials costs.

SECTION VII
LITERATURE STUDY

Wet electrostatic precipitators have been used in the metallurgical and chemical industries for many years. Information on the design and application of WESP's in the industries with the highest usage was accumulated by SRI under Contract CPA 22-69-73. This information has been updated and expanded where appropriate, and is presented in the following sub-sections.

IRON AND STEEL INDUSTRY

Introduction[11,12]

On the basis of existing evidence, the deliberate smelting of ore to produce iron began between 1350 B.C. and 1100 B.C. over a wide geographic area. In America an iron works was established in Virginia on the James River about 1619; this was destroyed in an Indian raid in 1622 and never rebuilt. The Hammersmith (now Saugus), Massachusetts iron works was begun in 1645 and was the first successful iron works in this country. Iron was then produced by the reduction of iron ore in charcoal furnaces. The blast furnace was introduced into England about 1500 A.D. Coke was first used as a blast-furnace fuel in England in 1619. About 200 years later - again in England - the principle of heating the air before it was blown into the furnace was introduced, hence the term "hot blast". The Bessemer steelmaking process eventually supplanted all techniques before it. Closely following the Bessemer process was the development of the regenerative-type furnace that, now known as the open-hearth furnace, became adapted to steel-making and evolved into the principal means for producing steel throughout the world. Although the Bessemer converter production exceeded that of the open-hearth until 1908, the latter grew rapidly until, in the 1950's, 90% of the steel produced in this country was by the open-hearth process. A third process, the electric furnance, is a relative newcomer to the field of steelmaking and is gradually finding more and more applications in the quantity production of quality steels. The most recently developed steelmaking method is a pneumatic process that involves blowing high-purity oxygen onto the surface of a bath of molten pig iron, a method known as the basic oxygen furnace (BOF), or LD process. Estimates for 1980 show about 25-30% of the steelmaking will be carried out in electric furnaces, 65-70% by the BOF process, and 5% by the open-hearth process. The Bessemer converter has essentially disappeared as a steelmaking method. A typical steel plant operation in which there are about 10 major areas requiring dust or fume control equipment is shown as a flow chart in Figure 29. Each of these areas will be discussed in detail in subsequent

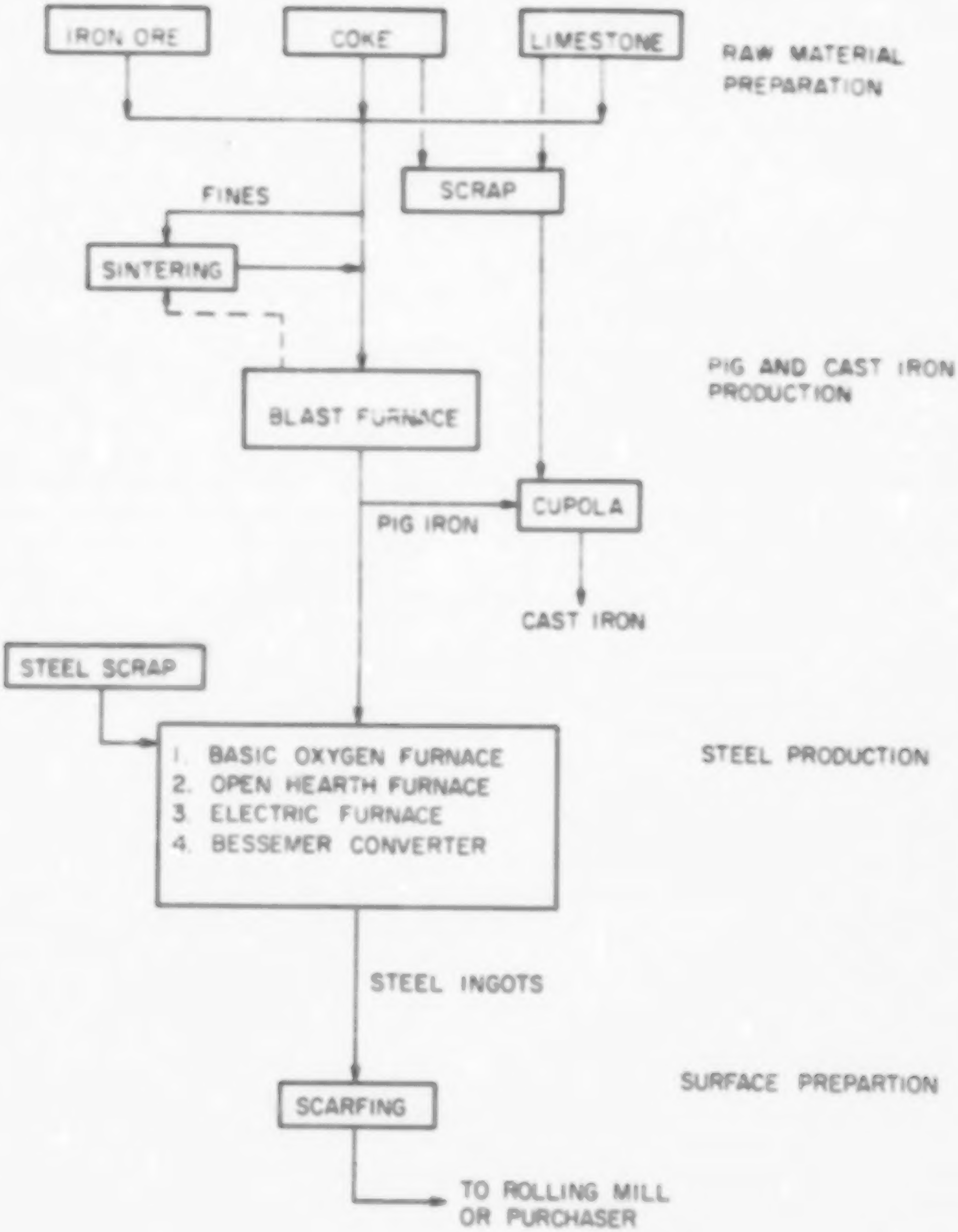

IRON ORE
COKE
LIMESTONE
RAW MATERIAL PREPARATION
SCRAP
FINES
SINTERING
PIG AND CAST IRON PRODUCTION
BLAST FURNACE
CUPOLA
PIG IRON
CAST IRON
STEEL SCRAP
1. BASIC OXYGEN FURNACE
2. OPEN HEARTH FURNACE
3. ELECTRIC FURNACE
4. BESSEMER CONVERTER
STEEL PRODUCTION
STEEL INGOTS
SURFACE PREPARTION
SCARFING
TO ROLLING MILL OR PURCHASER

Figure 29. A Flow Chart Showing the Steps in the Steelmaking Process From the Basic Raw Material and Scrap Input to the Finished Product.[4]

sections with emphasis on process parameters relating to the use of wet electrostatic precipitators. Coke oven gas detarring will be discussed in a section describing collection of mists.

Blast Furnace

The blast furnace is a cylindrically-shaped structure made of steel and lined with refractory brick, usually about 100 feet tall and 25-35 feet in diameter. Near the bottom are nozzles or "tuyeres" through which preheated air is blown into the furnace under pressure. The raw materials used in the production of pig iron are semi-continuously charged into the blast furnace. The charge consists of iron-bearing materials (iron ore, sinter, pellets, mill scale, open-hearth or Bessemer slag, iron or steel scrap, etc.), fuel (coke), and flux (limestone and/or dolomite), and is introduced into the top of the furnace through two successive cone-shaped valves, at least one of which is always closed. The shape and location of the lower valve (or bell) is such that the charge is deposited uniformly around the circumference of the furnace near the walls. As the charge melts, or is burned in the lower region of the furnace, the stock column gradually settles, thus leaving room for additional charges at the top. The reducing atmosphere necessary for reduction of iron ore is generated by a reaction between the precharged coke and preheated air (1000-1700°F). The air may be enriched with natural gas, fuel oil, or oxygen. As the blast rises through the burden, it reacts exothermically with the coke to produce the high temperature reducing gases which react with the iron oxide to produce molten pig iron. The reduction reactions can be summarized as a single reversible reaction as follows:

$$Fe_2O_3 + 3CO \rightleftarrows 2Fe + 3CO_2$$

The presence of an excess of carbon monoxide keeps the equilibrium shifted to the right. The molten iron and slag collect in two layers at the bottom of the furnace, the less dense slag floating on the iron and protecting it against oxidation. The slag is occasionally withdrawn from the furnace, and several times a day, the molten iron is withdrawn through a tap hole into a large ladle lined with fire brick that holds several hundred tons of the hot metal.

The gases which pass through the charge leave the top of the furnace through four "off takes" arranged around the dome, and pass through a brick-lined downcomer to the dustcatcher, which is a large settling chamber. The coarser dust particles settle in the low gas velocity regions of the settling chamber.

The particulate material emitted during normal operation of the blast furnace originates from several sources, including dirt and other fines in the charged ore, the dust caused by the downward abrasive action of the burden through the furnace, and coke and limestone dust. These particulates are carried out of the furnace by the gas stream, and dust loadings range from 7 to 17 gr/scf.

A troublesome source of blast furnace emissions is that occurring during a burden "slip". Slips are sudden movements of the burden in the furnace occurring when a portion of the burden forms a bridge within the furnace. The underlying burden continues to melt and settles under the bridge and the gas pressure increases. When the bridge opens or slips, a large volume of gas suddenly passes through the furnace system and carries with it great quantities of the lighter portions of the stock.

Two emissions come from the top of a blast furnace; top gas and the dust which it entrains. After passing through the charge the gases which leave the furnace at a temperature of around 300°F, have a composition typically as follows:

Constituent	Volume %
CO	26.2
CO_2	13.0
H_2	1.9
CH_4	0.2
N_2	58.7

The particulate material emitted during normal operation of the blast furnace comes from several sources, including dirt and other fines in the charged ore, the dust developed by the downward abrasive action of the burden through the furnace, and coke and limestone dust.[13]

The output of particulate material from blast furnace operations is primarily dependent on the physical characteristics of the charge. For example, the burden can range from unscreened ore to that consisting mainly of sinter, pellets, or mixtures of sinter and pellets. Different combinations of burden, fuel, and air can be used to effect different output characteristics. Sinter and pelletized ore, when used as a charge material, naturally effect a marked reduction in dust product as compared to either screened or unscreened ore, because of the improved physical characteristics. A good illustration of this is shown in Figure 30, where the amount of dust from a furnace is shown as a function of the amount of sinter in the charge.[14]

One of the major reasons industry cleans blast furnace gas is to render it sufficiently clean for heating coke ovens, boilers,

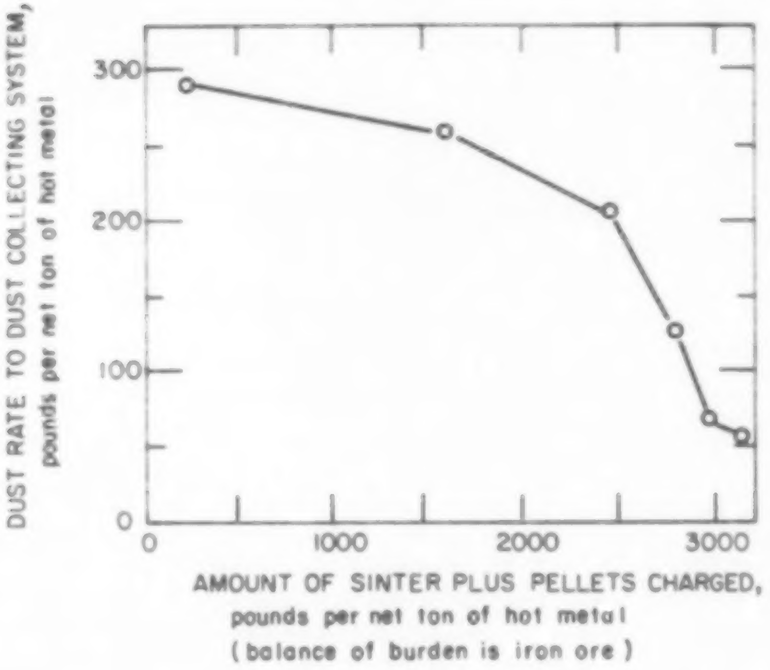


Figure 30. Effect of Burden Improvement on Dust Rate From A Blast Furnace to its Dust Collecting System[14]

stoves, soaking pits, and gas engines. The gas has a heating value of about 100 Btu/cf, but must be cleaned before being used successfully.

During normal blast furnace operations, the dust loading of the gas leaving the furnace is in the 7-10 gr/scf range although loadings as high as 17 gr/scf have been reported. For each 1000 tons of hot metal produced, about 100 tons of particulate is expected. From a 1400 ton-per-day furnace, Bishop reports 68% coarse flue dust and 32% fine.[15] The coarse dust to which he referred was removed by greatly reducing the velocity of the gas, and at the same time, suddenly changing the direction of the gas stream. The dust for the above mentioned plant contained around 30% iron, 15% carbon, 10% silicon dioxide, and small amounts of aluminum oxide, manganese oxide, calcium oxide, and other materials.

A typical chemical composition of blast furnace effluent is difficult to supply since the composition varies so greatly as shown in Table 13.[16] However, the major constituents and the usual composition range is as follows: 35-50% iron, 8-13% silica, 2-5% alumina, 3-4% calcium oxide, 3-10% carbon, and small amounts of alkali elements, phosphorus, zinc, lead, sulfur, and other trace elements. Some additional data on the chemical composition of dust samples taken from the dust catchers, wet scrubbers, electrostatic precipitators, and dust leaving the precipitator are given in Table 14.[17] The material collected in flue dust catchers and washers has a high iron content, and after agglomeration, becomes a suitable material for recharging. Precipitator dust contains less iron and several objectionable impurities. Particle size distributions of blast furnace dust also varies depending on the type of ore being charged into the furnace and prior beneficiation. Table 15 presents a range of observed particle size distributions.

As stated earlier, blast furnace gas must be cleaned prior to utilizing its heating value in order to prevent clogging of burners, gas mains, and other maintenance problems. In a typical installation, gas from a blast furnace is generally cleaned as follows. Upon leaving the furnace, gas is passed through a dust catcher which removes particles larger than a few hundred microns (50-70% by weight), leaving a dust concentration in the gas of 3-6 gr/scf. From the dust catcher, the gas is further cleaned in a two-stage plant. The first stage consists of a primary cleaner to separate the coarse fractions and a secondary cleaner to separate the fine dust. A typical combination of a two-stage cleaner consists of a wet scrubber and a wet electrostatic precipitator in series. Typical dust concentrations for the gas at various points in a modern gas-cleaning system are:

Table 13[16]

Chemical Analysis of Blast Furnace Flue Dusts

Components	Weight Percent		
	Range for Several U. S. Plants	Midwest Plant	Range for Several European Plants
Fe	36.5 - 50.3	47.10	5.0 - 40.0
FeO	n. a.	11.87	n. a.
SiO_2	8.9 - 13.4	8.17	9.0 - 30.0
Al_2O_3	2.2 - 5.3	1.88	4.0 - 15.0
MgO	0.9 - 1.6	0.22	1.0 - 5.0
CaO	3.8 - 4.5	4.10	7.0 - 28.0
Na_2O	n. a.	0.24	-
K_2O	n. a.	1.01	-
ZnO	n. a.	0.60	-
P	0.1 - 0.2	0.03	0.3 - 1.2
S	0.2 - 0.4	n. a.	- 0.1
Mn	0.5 - 0.9	0.70	0.3 - 1.5
C	3.7 - 13.9	n. a.	5.0 - 10.0
Pb	n. a.	n. a.	0 - 15.0
Cu	n. a.	n. a.	trace
Alkali	-	-	0 - 20.0
Zn	n. a.	n. a.	0 - 35.0

Table 14[17]

Weight Percent Composition of Dust Samples from Blast Furnace Gas Cleaning Plant

Sample Components	Deposit from primary dust catcher	Deposit from secondary dust catcher	Deposit from washers	Dust in gas leaving washers	Deposit from precipitator	Dust in gas leaving precipitator	Deposit in power station burners
Insol.	8.50	11.60	9.40	13.68	22.60	11.44	
Fe_2O_3	75.43	53.00	61.30	14.40	19.30	8.64	3.52
Al_2O_3	1.80	1.55	4.35	6.91	15.58	6.70	
MnO	0.62	0.60	0.63	2.16	1.10	1.49	
CaO	1.60	2.40	3.56	6.36	7.12	4.68	2.80
MgO	0.80	1.09	1.67	8.04	9.90	9.28	3.04
P	0.24	0.20	0.41	0.54	0.71	0.57	0.14
S	-	-	0.41	1.89	1.33	1.37	0.36
Cl	trace	trace	nil	1.32	0.20	3.44	29.22
Zn	nil	nil	nil	1.20	0.90	1.20	0.70
Na_2O	0.28	0.32	0.25	9.25	1.55	9.75	5.80
K_2O	0.56	0.92	0.55	20.90	2.70	22.40	36.15
Loss on ignition	5.90	23.50	15.65	-	15.95	-	9.06

Table 15[17]

Size Analysis of Blast Furnace Flue Dust

Screen Size		Dust Loading
Mesh	Microns	Range, %
20	833	2.5 - 20.2
30	589	3.9 - 10.6
40	414	7.0 - 11.7
50	295	10.7 - 12.4
70	208	10.0 - 15.0
100	147	10.2 - 16.8
140	104	7.7 - 12.5
200	74	5.3 - 8.8
-200	-74	15.4 - 22.6

at top of furnace	7-13 gr/acf
dust catcher outlet	3-6 gr/acf
after primary washer	0.05-0.7 gr/acf
after electrostatic precipitator	0.005-0.01 gr/acf

Wet electrostatic precipitators are normally used for secondary blast furnace gas cleaning since the gas delivered to the blast furnace precipitator has been cooled to saturation. The type most widely used is a vertical flow employing pipes of 8-inch or 12-inch diameter as collecting electrodes. Plate-type collecting electrodes with horizontal flow have also been used. A rather unique plate-type with vertical flow example is located in the Usinor-Dunkirk steel plant in France.[18]

In this plant the primary gas cleaning consists of dust catcher with a diffusor cone where deposition occurs by gravity and two cyclones in parallel with a rectangular and tangential gas outlet. The wet secondary cleaning consists of three secondary cleaning lines from the two cyclones. Each line carries a scrubber and wet electrostatic precipitator. The scrubber is a simple tower in which the atomized water travels in the opposite direction of the gas stream and its essential task is to lower the gas temperature from about 200°C to 30°C. Each precipitator consists of a vertical cylinder, divided into two parts which can be isolated in operation by a damper. Each section contains a group of vertical plates at a distance of 25 cm and in the form of a rectangle. Between each plate are suspended ionizing filaments fixed at the top to heated high voltage insulators. The plates are suspended at the top from tubes through which the water, which streams down the plates, is supplied. Intensive periodic spraying reinforces the cleaning operation. For the three lines, and with maximum feed rate, the grain loading after cleaning is 0.0028 grains/cu. ft.

A fairly new innovation by Lurgi known as the "Venturion Electro-Precipitator"[19], combines venturi scrubbers and the wet precipitator in a common housing to meet the demand for additional space economy. Other advantages are less consumption of water resulting in lower investment cost for the water treatment equipment, and elimination of scrubbing tower foundations. Precipitators of this type have been installed at Yawata's Kukioka (Japan) blast furnace and at the Tobata (Japan) No. 3 blast furnace with excellent results. With inlet gas concentrations between 2.51 and 5.02 grams/Nm^3, collection efficiencies averaged greater than 99.9%.[20] Compared in cost to the dry Cottrell and the normal wet-precipitator-spray tower combination, the "Venturion-Precipitator" costs considerably less (about 30%) than the Cottrell and slightly less (about 10%) than the normal arrangement.

The more typical wet type pipe electrostatic precipitator is shown in Figure 31. In some designs the pipes are suspended from a header sheet at the top, with the lower end unsupported, allowing the gas to surround the pipes. In other designs, a lower header sheet is used to prevent the gas from surrounding the pipes. Discharge electrodes are usually vertically hung, twisted square bars (3/16 - 1/4 in.) spanning the height of the collecting electrodes. Rapping the electrodes to dislodge dust is not required since the collectors are flushed with liquid. An overall flow diagram of wet cleaning blast furnace gas with a wet precipitator is given in Figure 32. Of the 60 blast furnaces at present on basic iron production in the British Steel Corporation, all but seven use this three-stage cleaning system.[21]

Trends in the application of electrostatic precipitators for cleaning blast furnace gas are indicated by the number of installations from 1931 to 1968 as shown in Figure 33, which presents the number of furnaces and the number of furnaces with electrostatic precipitators installed. Precipitator inlet gas temperatures and inlet particulate loading are shown in Figures 34 and 35. Distribution of precipitator gas velocity, field strength, and power are shown in Figures 36, 37, and 38, and design efficiency trends are given in Figure 39.

Figure 40 is a plot of the efficiency of blast furnace precipitators as a function of the collection plate area to gas volume ratio. The range of design values is given by the curves, and test data are plotted individually as points. The design data would give precipitation rate parameters ranging from about 9-11 cm/sec (0.3-0.37 ft/sec). Test data show a fairly wide scatter band. Design values of precipitation rate parameter w for pipe-type blast furnace precipitators are usually in the range of 0.25 to 0.45 ft/sec, while performance values of w tend to be somewhat higher. Figure 41 gives more detail on the comparison of design and actual performance by using as a basis of comparison the ratio (R) of actual performance w to the anticipated performance w. For instance, a value of R = 1.20 means that the precipitator size is 20% larger than required to meet the expected performance for that particular unit.

Electric Arc Furnaces

Electric arc furnaces employed for melting and refining steel are cylindrical, refractory-lined structures. They range in size from a diameter of about seven feet, with a hot metal capacity of about four tons, to a diameter of 24.5 feet with a capacity of 200 tons. The refractory lining used inside the steel structure may be either

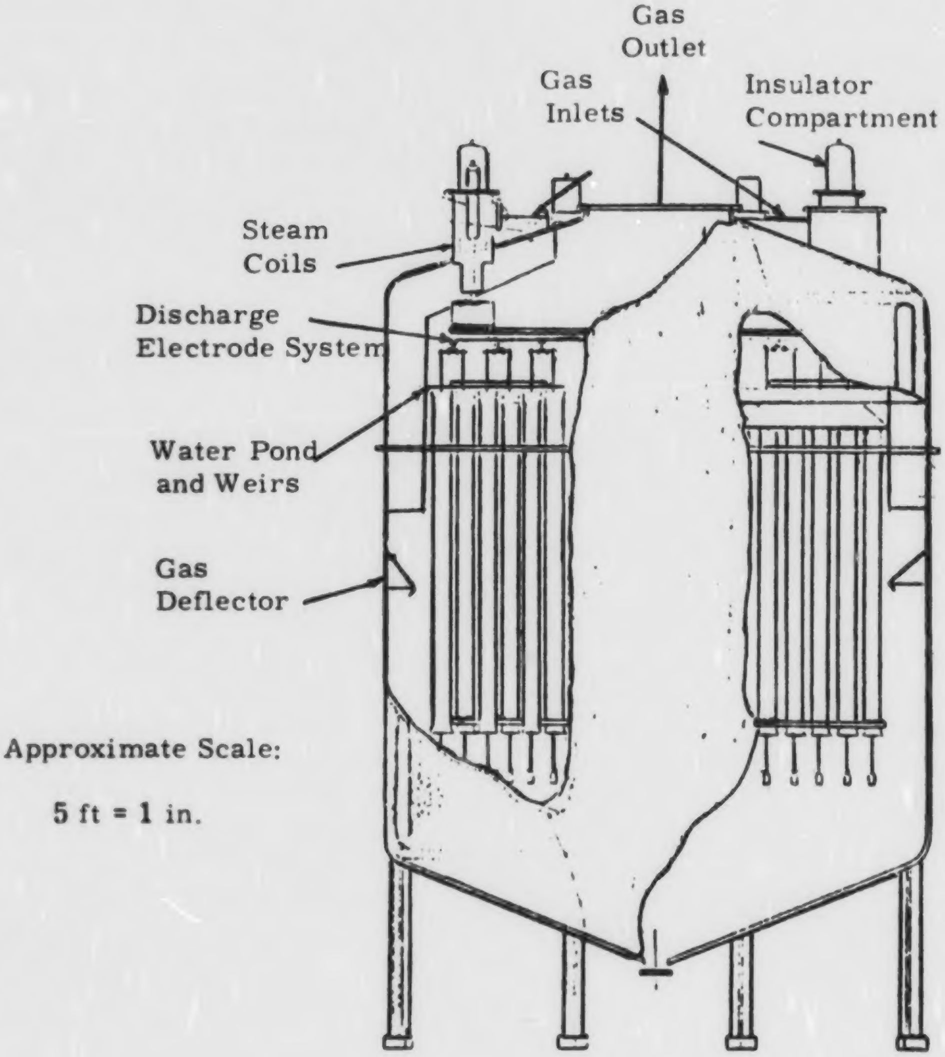

Gas
Outlet
Gas
Inlets
Insulator
Compartment
Steam
Coils
Discharge
Electrode System
Water Pond
and Weirs
Gas
Deflector
Approximate Scale:
5 ft = 1 in.

Figure 31. Typical Wet Type Pipe Precipitator for Cleaning Blast Furnace Gases.[17]

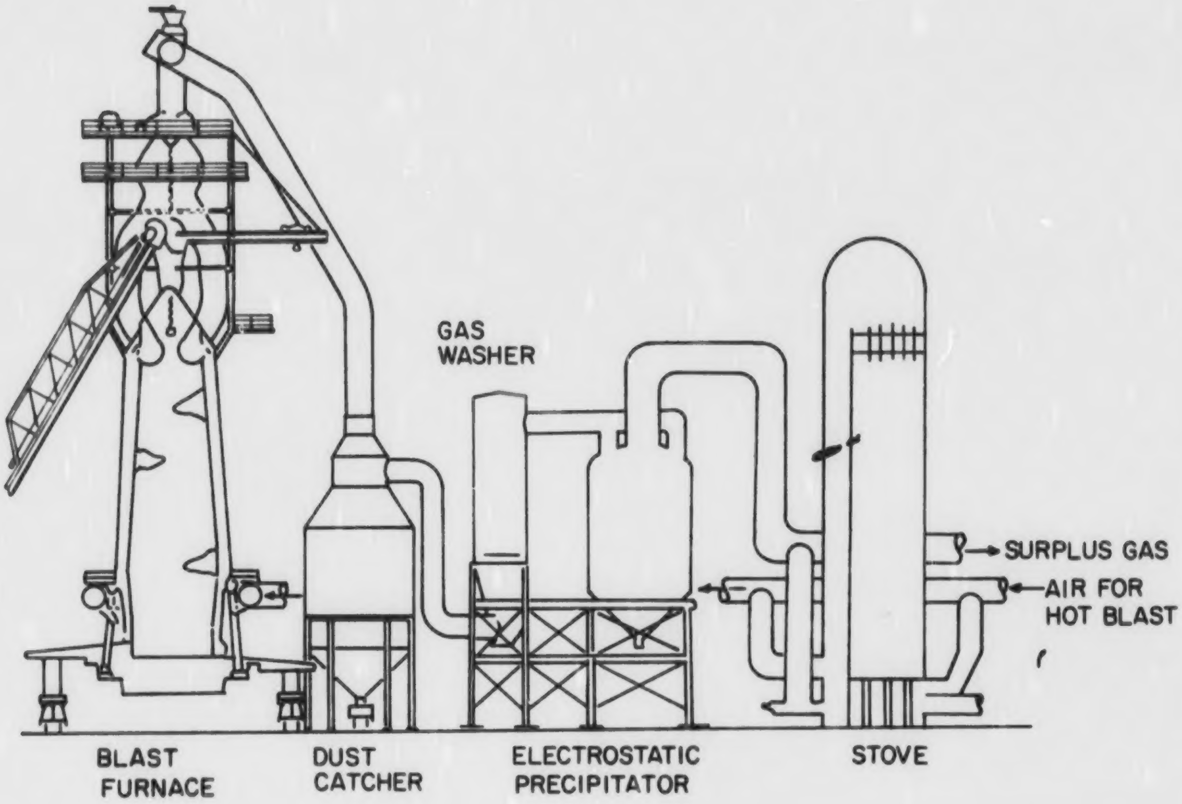

GAS
WASHER
SURPLUS GAS
AIR FOR
HOT BLAST
BLAST
FURNACE
DUST
CATCHER
ELECTROSTATIC
PRECIPITATOR
STOVE

Figure 32. Flow Diagram for Wet Cleaning Iron Blast Furnace Gas with Electrostatic Precipitator[21]

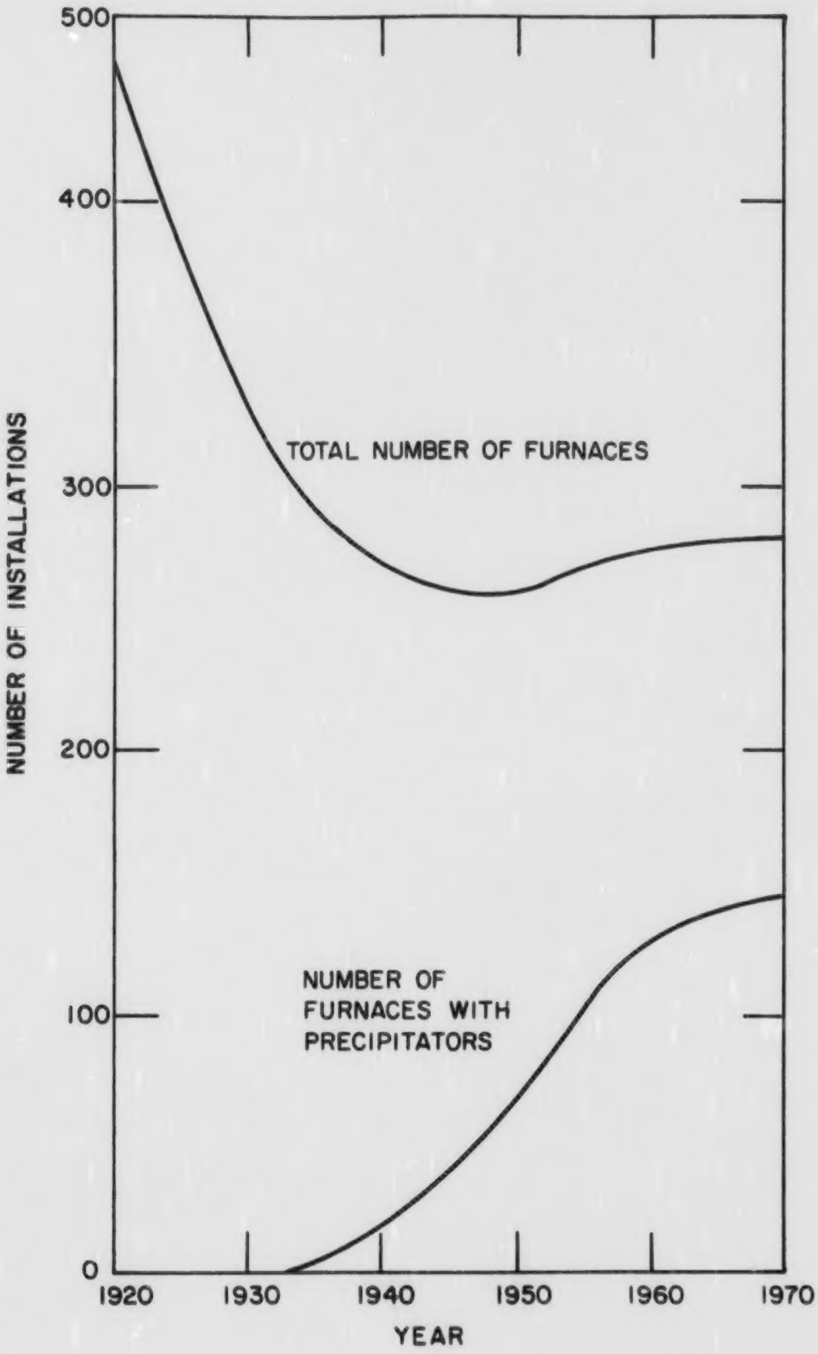


Figure 33. Blast Furnace Statistics for Period 1920-1969.[38]

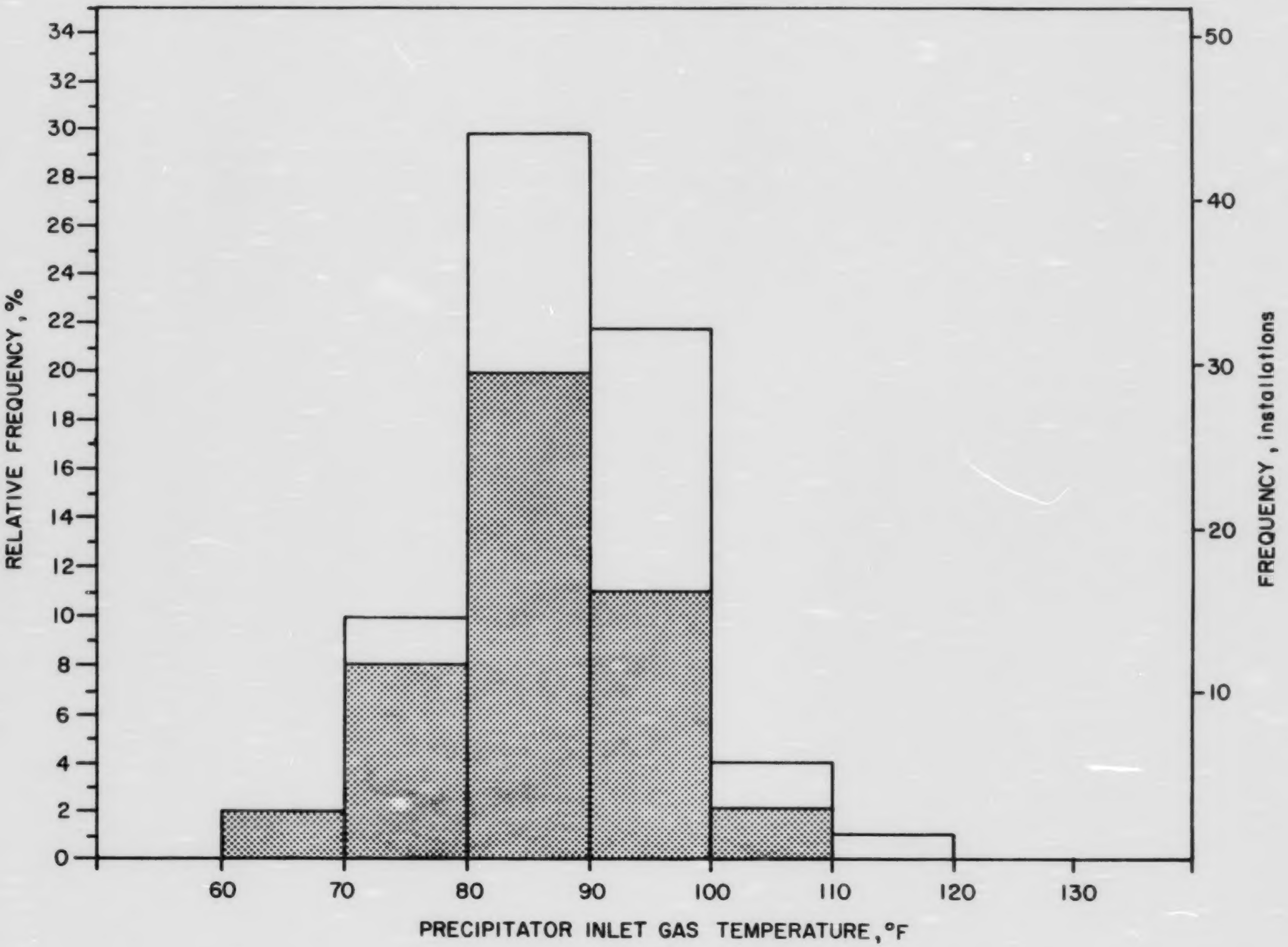


Figure 34. Distribution of Precipitator Inlet Gas Temperature. Blast Furnace Installations.[38]

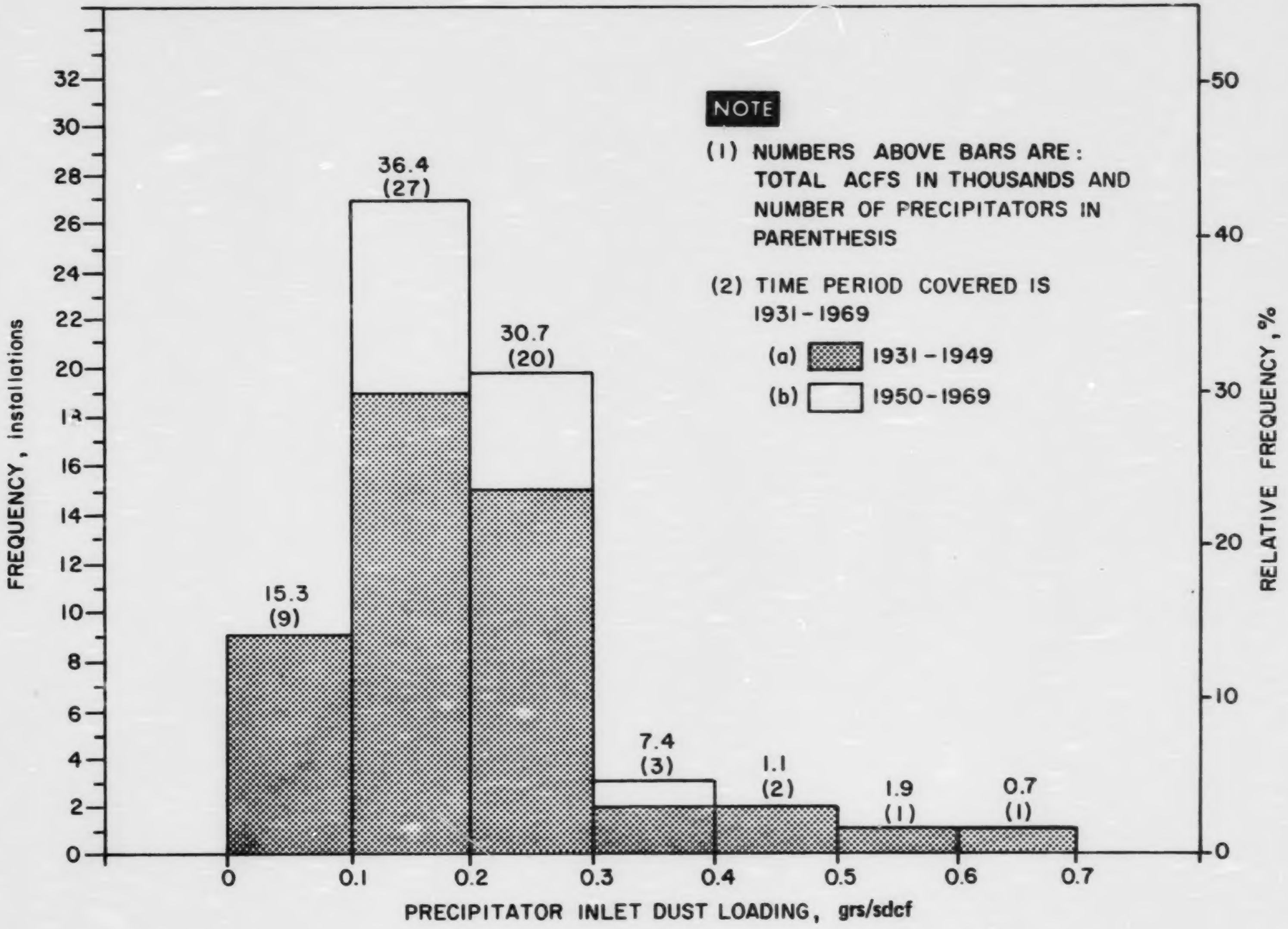


Figure 35. Distribution of Precipitator Inlet Dust Loading. Blast Furnace Installations.[38]

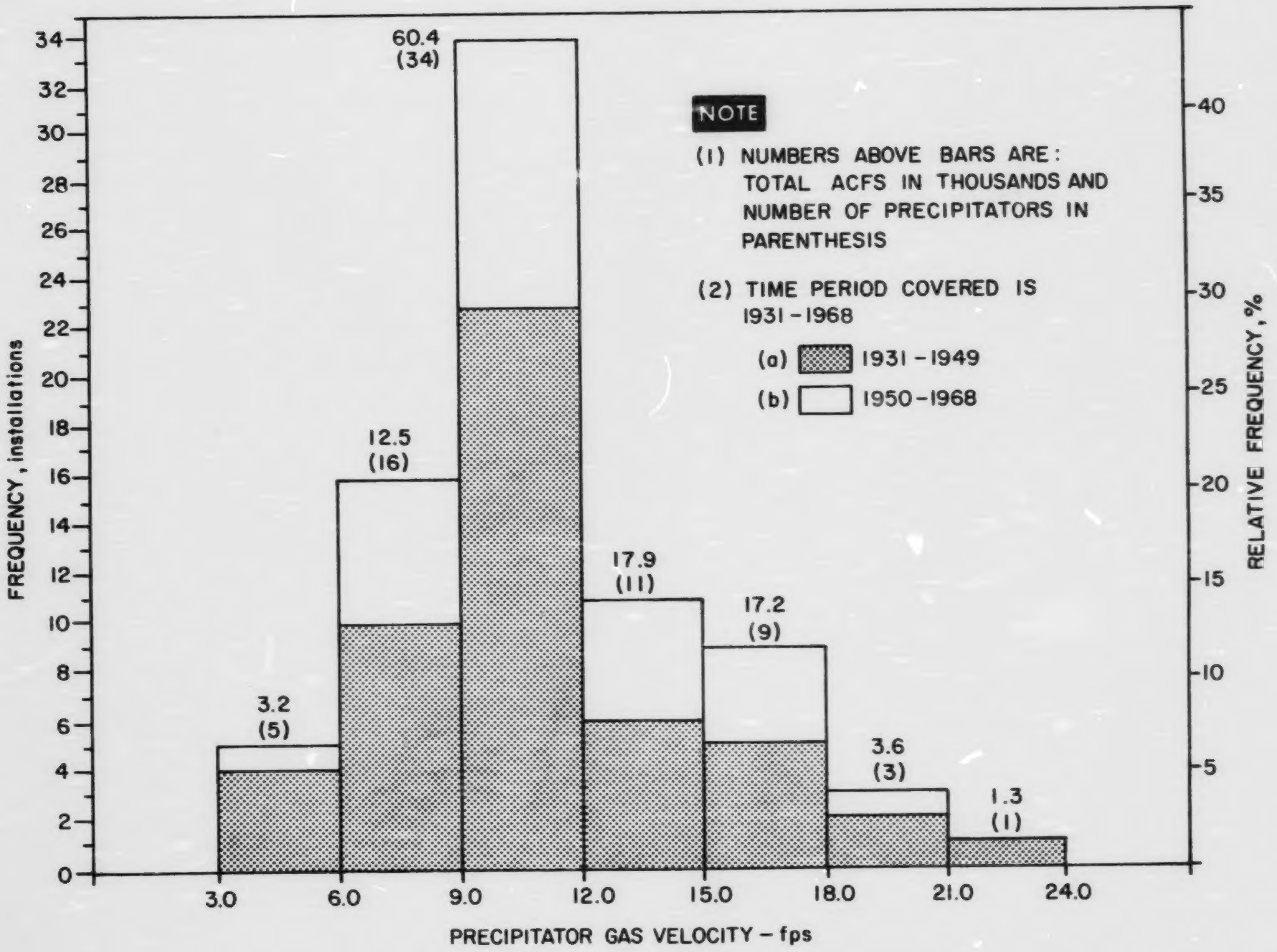


Figure 36. Distribution of Precipitator Gas Velocity. Blast Furnace Installations.[38]

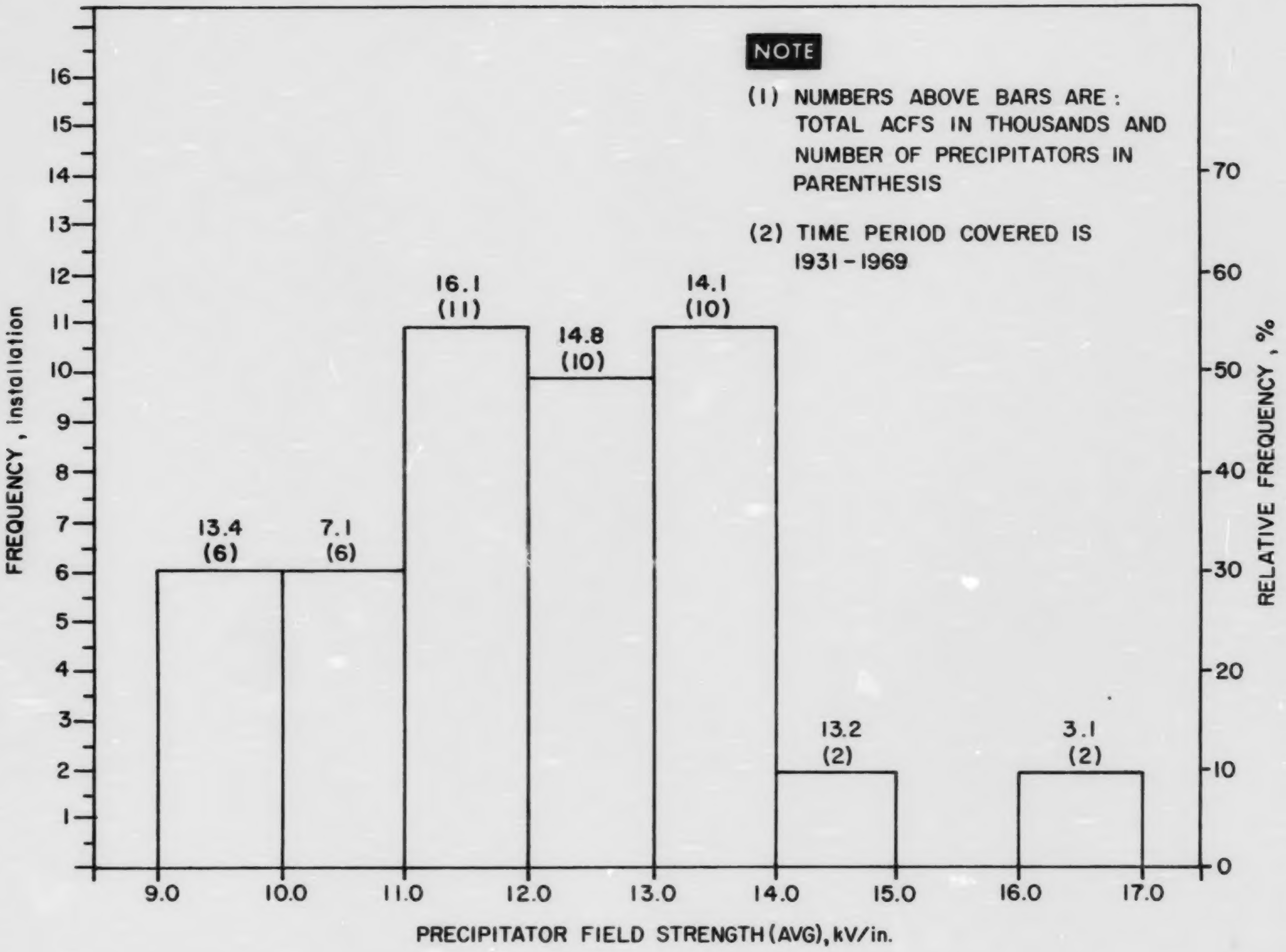


Figure 37. Distribution of Precipitator Field Strength. Blast Furnace Installations.[38]

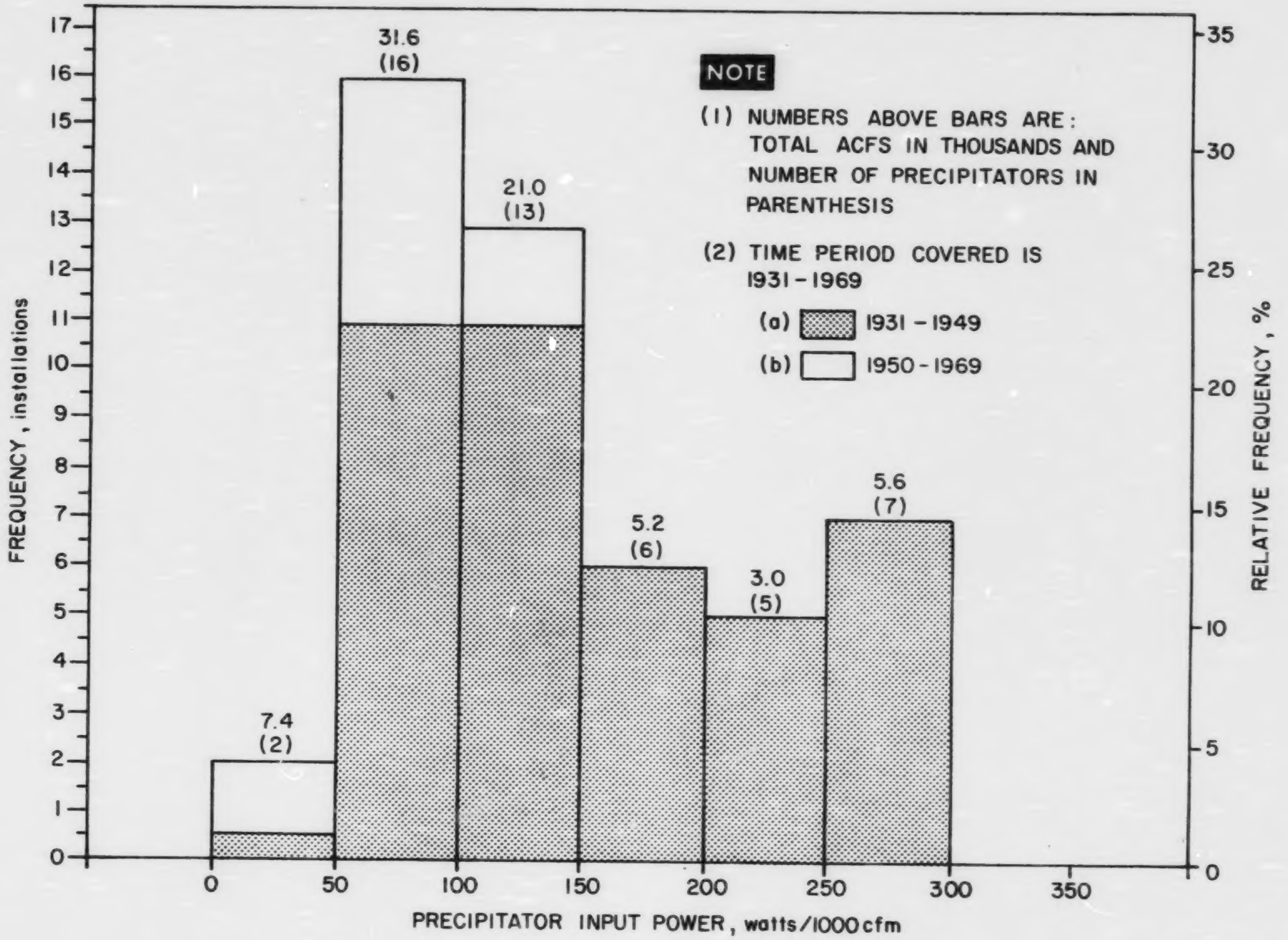


Figure 38. Distribution of Precipitator Input Power. Blast Furnace Installations.[38]

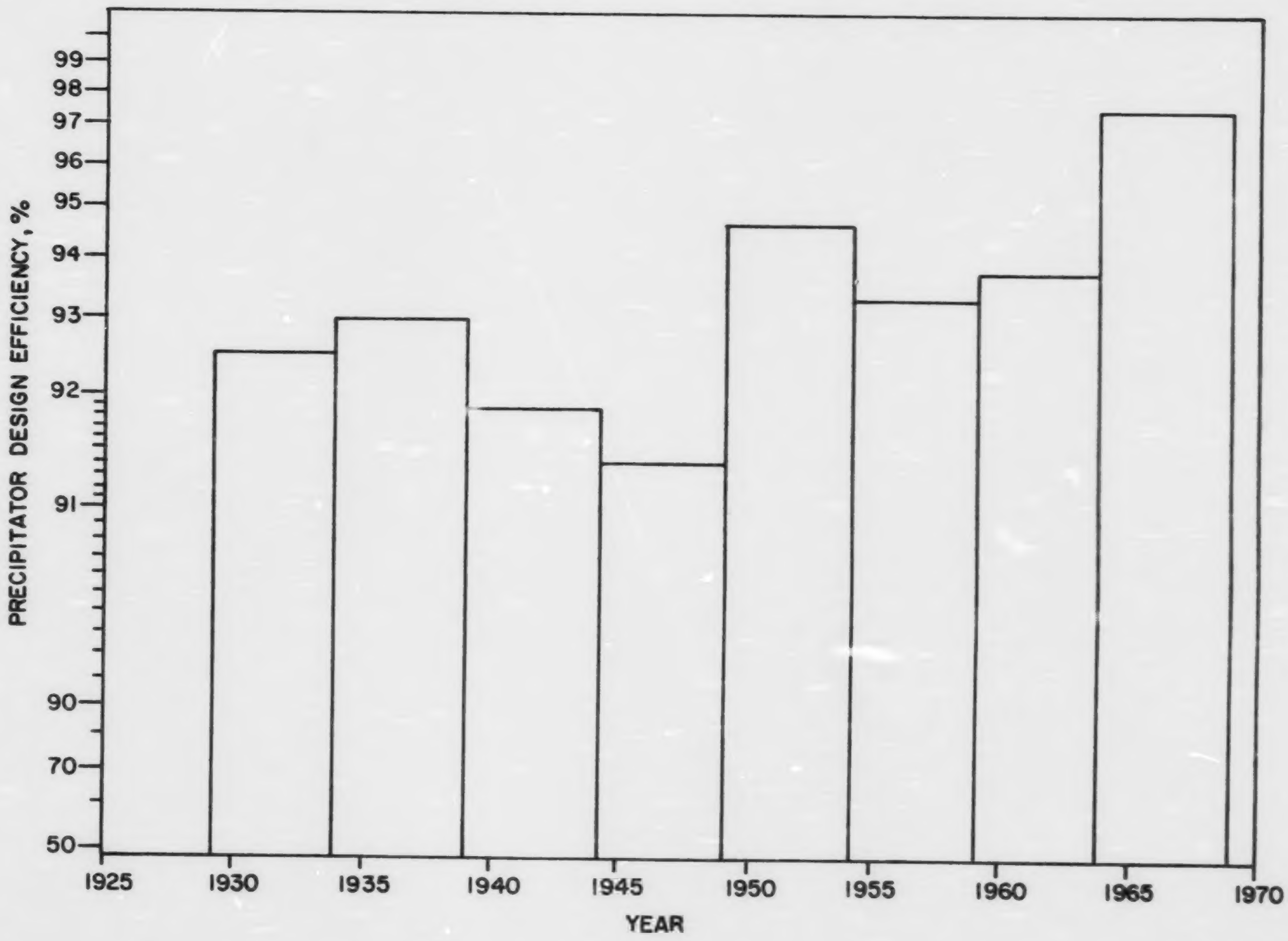


Figure 39. Design Efficiency Trends Over the Period 1939-1969 Prorated on acfm Basis for Blast Furnace Installations.[38]

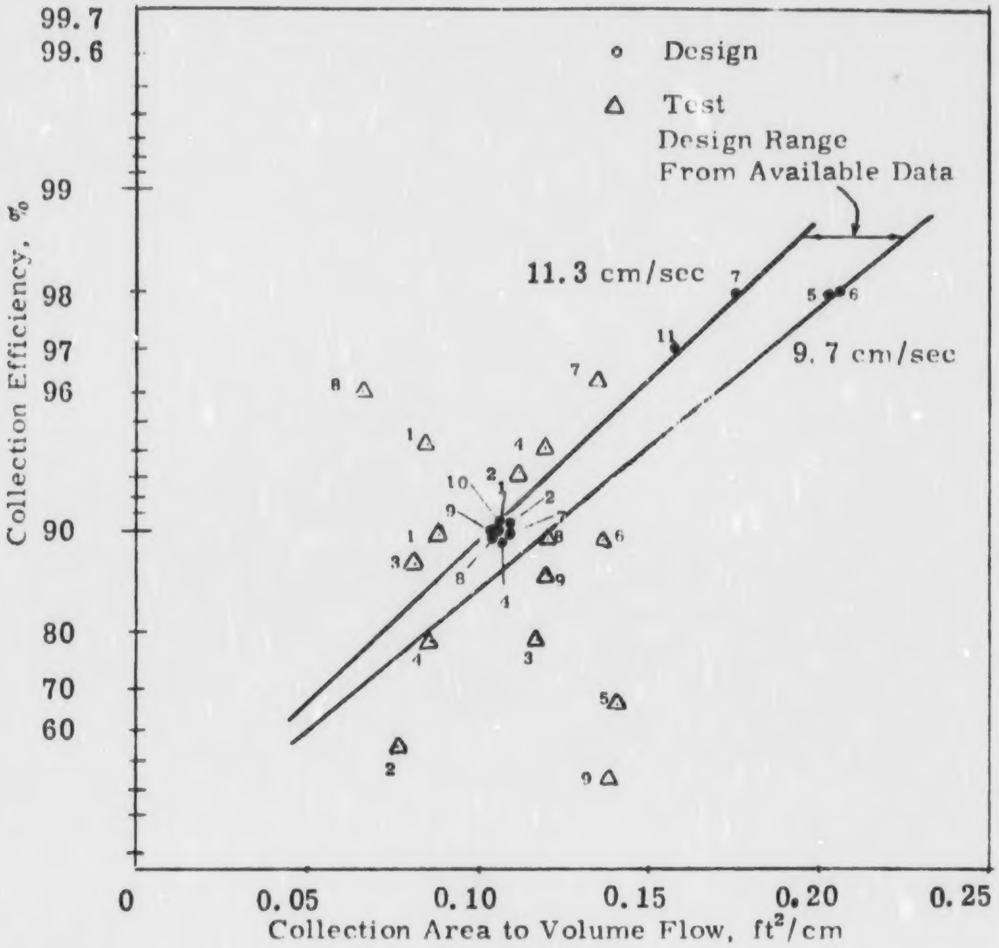


Figure 40. Relationship Between Collection Efficiency and Specific Collection Area for Electrostatic Precipitators Operating on Blast Furnace Installations.[17]

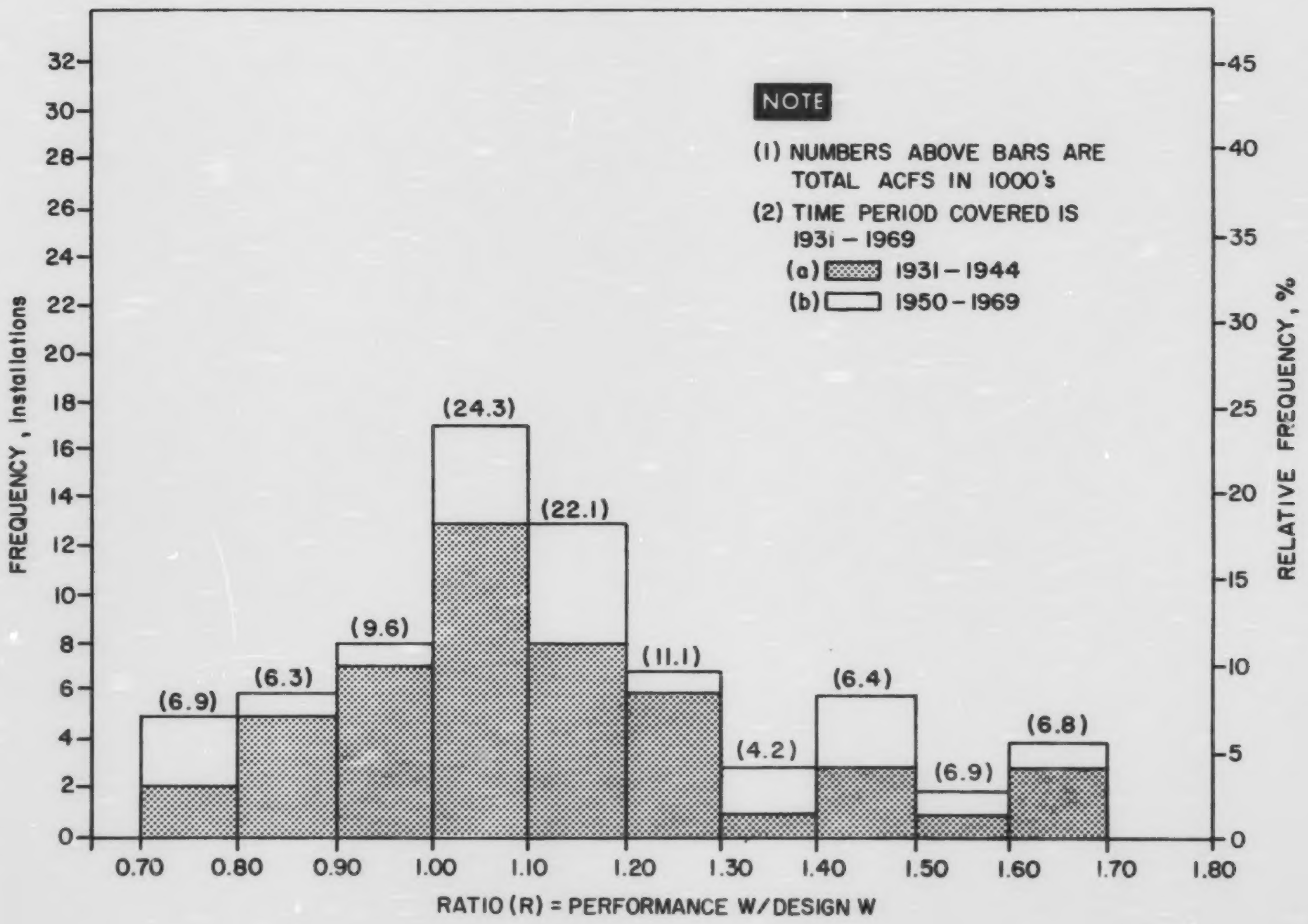


Figure 41. Comparison of Actual Performance to Design Performance on Blast Furnaces (Basis: ratio of precipitation rate parameters using Deutsch equation).[38]

acid or basic, but basic refractories are more commonly used. Because of the flexibility of operation, the electric arc furnace is used to produce steels with a wide range of composition, including carbon, alloy, and stainless grades. In 1970, 15.3% of the steel produced in the U.S. was produced in electric arc furnaces.[22]

In practice, steel scrap, and perhaps hot metal from a blast furnace, are charged into the furnace, the electrodes lowered, and the power turned on. Power for melting and super-heating the charged material is supplied to the furnace through externally supported carbon electrodes which are automatically raised or lowered through holes in the furnace roof. Intense heat is produced by the current arcing between the electrodes and the metal charge, and this, coupled with the resistance heating that occurs as the current flows through the charge materials, results in melting and super-heating of the charge.

Very little air is admitted to the electric arc furnace during the meltdown period, and during this time the furnace operates with an atmosphere containing a small amount of carbon monoxide.[23] The particulate emissions from the electric arc furnaces during this meltdown period are composed primarily of volatile matter from the charged scrap including oil, grease, and oxides of metals with high vapor pressures. Zinc oxide from galvanized scrap is probably the most common metallic oxide evolved during this period. When lancing occurs after meltdown, the oxygen combines with carbon, silicon, and manganese in the melt, to produce a furnace atmosphere containing primarily carbon monoxide (80%), free oxygen, carbon dioxide, and hydrogen. Reported exit temperatures vary from 1800-2900°F. Since the flue gases contain large carbon monoxide concentrations when released from the electric furnace, there is an explosion hazard and the gases must be burned or diluted with air before entering dust cleaning devices. The flue gas volume to be treated by a dust collecting device ranges from a minimum of 12 to perhaps 200 times the volume of oxygen lanced into the furnace, depending on the method used to cool and collect the waste gases.

Wide variations of emissions generated during electric furnace steelmaking are attributable to the physical nature of scrap used, the cleanliness of the scrap, the nature of the melting operation, and oxygen lancing. A compilation of data on total particulate emissions from various electric arc furnaces is given in Table 16.[24]

Just as the amount of particulate matter from the electric furnace varies with the charge and operating conditions, so does the composition of the particulate. Table 17 presents reported compositions of dust emissions.[25,26]

Table 16[24]

Electric Arc Steel Furnace Fume Emission Data

Case	Rated Furnace Size, tons	Average Melting Rate, tons/hr	Cycle Time, hr	Fume emission/ton Melted, lb/ton	Furnace Process
A	50	18.3	4	9.3[3]	
	75	23.5	4	18.6[4]	Basic, single slag
	75	23.5	4		
B	50[1]	14.4	4	7.6	
	50[1]	13.6	4	6.9	Basic, single slag
	75[1]	21.9	4	12.3	
	3	1.5	2	12.6	Acid, oxygen blow
	3	1.1	2	7.6	Acid, oxygen blow
	6	3.1		10.4	
	10	6.6	2	5.5	Basic, oxygen blow
	10	5.4	2	5.2	Basic, oxygen blow
	2[2]	1.5[2]		13.4	
C	3	1.9	2	4.5	Acid
	3	1.6	2	5.8	Acid
	3	1.9	2	5.7	Acid
	6	2.6	2.3	15.3	
	6	3.0	2	12.8	
D	18	5.4	3	6.1	
E	6	4.1	1.2	29.4	Acid, single slag
F	3	1.8	1.8	12.7	Acid, single slag

---

[1] Refer to same furnaces as Case A.

[2] Two 2-ton furnaces operating in parallel.

[3] Average for one 50-ton and two 75-ton furnaces processing normal scrap.

[4] Average for one 50-ton and two 75-ton furnaces processing dirty, subquality scrap.

Table 17[25,26]

Electric Furnace Dust Composition

Component	Weight, %
ZnO	37
Fe	25
CaO	6
MnO	4
Al_2O_3	3
SO_3	3
SiO_2	2
MgO	2
CuO	0.2
P_2O_5	0.2

Dust from electric arc furnaces tends to be extremely fine as indicated in Table 18. These data, from several sources, indicate that 70 to 100% of the fume is below 5.0 microns in size.

Because of the small particle size of arc furnace fume, only three types of cleaning equipment, bag filter, venturi scrubber, and electrostatic precipitator, are considered. A British Steel Corporation survey in 1969 indicates the distribution of utilization of these collectors for arc furnace fume.[29] As shown in Table 19, there is a strong preference in the United Kingdom to use wet precipitators on the larger arc furnaces. High energy wet scrubbers are increasingly used for 20-30 ton furnaces while bag filters are used mostly on small furnaces. A paper by Holland and Whitwam[30] deals with the design problems involved in providing a suitable technique (in this case, wet precipitation) to overcome the difficulties of providing direct roof extraction for a large (100 ton) electric furnace using high rates of tonnage oxygen. Pilot plant tests at the plant described in the paper left a choice of two types of cleaning equipment as best for a large plant - venturi scrubber and wet electrostatic precipitator. The venturi scrubber was eliminated because of the large pressure drop (30 in. wg) and the necessity for varying the throat to maintain the pressure drop at the varying volumes. The operating conditions which had to be met are listed below:

maximum oxygen usage	2300 cfm NTP
maximum gas volume	35,000 cfm NTP
maximum dust burden	6.5 grains/cf NTP
particle size	90% < 1 μm
maximum gas temperature	1250°C during lancing 1000°C during refining and melting
volumes at NTP	lancing 35,000 cfm melting 15,000 cfm refining 0-5000 cfm

The wet precipitator is of the horizontal gas-flow type with two fields in series connected to a high-voltage supply from one transformer selenium rectifier equipment with transductor control. If an electrical fault develops in the precipitator, either of the two fields can be isolated from the high voltage supply, which enables partial gas cleaning to be maintained until the fault is remedied. Stainless steel was used for the collecting and discharge electrodes, the casing was tile lined, and other mild steel surfaces in contact with the gases were protected with acid-resistant paint. Flushing of the precipitated materials is provided by means

Table 18

Electric Steel Furnace Fume Particle Size Data

Percent by Weight below Given Particle Diameter			
0.5 micron	1.0 micron	3.0 micron	5.0 micron
	90[1]		
95		100[1]	
90[1]			
			70[1]
			71.9[2]
			67.9[2]
			72.5[2]

[1] ESP Manual[27]

[2] Muhlrad, W., "Dust Extraction from the Fume of Electric Arc Furnaces", Iron and Coal 183, 669-675 (1961).[28]

Table 19[29]

FUME CLEANING FOR STEELMAKING PROCESSES 1969 (BSC)

Steelmaking Process	Electrostatic Precipitators Dry	Electrostatic Precipitators Wet	High Energy Wet Scrubbers	Bag Filters
LD, Kaldo, Rotor Converters	17	-	6	-
Open Hearth O_2 Lanced	32	-	-	-
Electric Arc Furnaces, O_2 Lanced				
up to 60 tons capacity	-	1	7	8
over 60 tons capacity	4	14	-	-

of oscillating water jets located above each field and their introduction is automatically sequenced to occur during the fettling and charging period on the furnace, when the precipitator is deenergized. The wash water is introduced at the rate of 1000 gal/min for a period of 7 minutes.

A fairly recent innovation in wet precipitator technology for cleaning electric furnace fume is described by Fraunfelder.[31, 32] This system consists of a hydro-scrubber (marble-bed scrubber) with a wet electrical precipitator arranged above it in the same housing. The fumes are pre-cooled at the scrubber inlet by direct water sprays and passed through a bed of marbles which is sprayed with water from below. The fumes then pass through the precipitator where final cleaning takes place. At predetermined intervals the plates are flushed for about three minutes. The power, supplied by standard selenium rectifiers, 55 kV, 750 mA, is maintained during flushing.

The pilot system having yielded good results, the ferro-silicon works of Valmoesa (Fraubunden, Switzerland) placed an order for an industrial collection system of this type to cope with a gas volume of 108,000 m^3/hr. With an initial dust loading ranging from 0.5 to 5.0 g/m^3 NTP, cleaning efficiency was measured as 98.4%. According to the findings of the Swiss Materials Testing Institute, the dust content of the clean gas ranged from 30-60 mg/m^3 NTP, averaging 37 mg/m^3 NTP.

Water requirements are 1400 l/min continuously for the Hydro-washer (scrubber) and an additional 1000 l/min during the three min per hour the nozzles for the precipitator are used. This gives an overall water consumption of 90 m^3/hr or 0.83 l/m^3 of gas treated.

Scarfing

Before steel can be rolled, surface defects in the bloom, ingot, and billets must be removed by scarfing, in which the skin of the steel slab is removed. In this operation, slabs from the slabbing mill are conveyed to the stationary scarfing machine, where they are preheated with oxygen and acetylene for about three seconds, after which the scarfing operation begins. The slabs pass the cutting torches at 80 to 120 fpm where a cut of about 1/16 inch is made on two sides of the slab. The sparks and fume are blown downward by compressed air toward a target plate which is continuously sprayed with water.

During the cutting operation a coarse, high pressure spray of water is introduced immediately after the gas nozzles to granulate the larger chips and wet the fume. Because of the high temperatures generated during the scarfing operation, some of the steel is vaporized and subsequently oxidized. The iron oxide fume is usually quite fine.

There are many references in the literature to wet precipitator usage for cleaning scarfing effluent, but little detail is provided concerning precipitator design and performance. A paper by Elliott and Lafreniere[33] is the best example of wet precipitator usage uncovered thus far. The Steel Company of Canada, Limited, Hamilton, Ontario, investigated various collecting equipment used elsewhere for similar applications and selected a tubular-type wet electrostatic precipitator. Since the gases entering the precipitator are saturated with water vapor, it was felt that the collected material could be more readily removed by water sprays than by mechanical shakers. The choice of a pipe-type rather than the plate-type precipitator was made to insure adequate water distribution during the washing cycle. Distribution weirs were installed as a precautionary measure to insure that the tubes were kept clean.

The precipitator installation consists of twin units in parallel designed to handle 70,000 cfm at dust loadings of 1.0 gr. per cu. ft. and maximum temperature of 150°F. Actual operating conditions indicate a flow of 56,000 cfm and temperatures varying between 40°F and 70°F. The precipitator consists of a group of 192, ten-inch diameter collecting pipes and 0.1055 inch diameter discharge electrode wires (#30 stainless) enclosed in two rectangular casings of 5/16 inch steel plate. All interior surfaces of the structure are epoxy coated and internal parts are made of stainless steel. Each electrode is supported from a centering clip attached to the electrode support framework, and the lower end of each discharge electrode is held taut by a 15 lb cast iron weight. A frame is provided to hold the bottom end of the electrodes in position. The upper framework is suspended from four insulators which are located in the respective insulator compartments. The entire framework including the electrodes is insulated from the grounded shell by these support insulators. To prevent dust and moisture from accumulating on the insulators, a heating and ventilating system is provided which consists of a fan and heater and the necessary ducts to the insulator compartments. Warm, dry air is blown into the compartments, and a thermostat maintains the temperature at about 200°F.

The collecting pipes are 10" in diameter by 15' long and constructed of 12 gauge #304 stainless steel. Each pipe is suspended from a stainless steel header sheet and held vertically in position by an alignment grid located at the lower end of the pipes.

The washing system consists of eight stainless steel full cone pattern nozzles located at the top of the casing. The power is on the precipitator at all times. After twenty blooms have been scarfed, the bloom scarf counter energizes a relay timer which energizes a wash timer which opens the water valve to the spray nozzles and closes the louvers at the entry to the exhaust fan. The louvers remain closed during the washing to reduce the gas flow to the precipitator and thus prevent carry-over of wash water out the stacks. The complete wash cycle is accomplished between scarfs and takes approximately 42 seconds to complete.

Cupolas[34]

The iron cupola is a moderately low cost, efficient method of continuously providing molten iron at the desired temperature and chemistry for foundry operations. The cupola is a cylindrical furnace lined with fireclay or firestone refractories which resemble a miniature blast furnace. It differs primarily in that pig iron and steel scrap replace iron ore in the charge. Since, in most installations, no water cooling is utilized in the melting zone, the lining has to be repaired between periods of operation. The charging door is located on the side of the cupola near the top. Legs support the cupola, thus permitting the use of a drop bottom which facilitates the removal of the remaining burden after the last charge has been tapped.

The charge is composed of coke, steel scrap, iron scrap, and pig iron in alternate layers of metal and coke with sufficient limestone being added to flux the ash from the coke to form slag. When properly mixed with the above materials and with sufficient combustion air, a self-sustaining exothermic reaction takes place due to burning of the coke, which provides the heat necessary to melt the charge. Blast air for combustion is blown in through tuyeres, located near the bottom of the furnace. The combustion air can be handled in one of two ways, depending upon the type of blast system used:

1. In the cold blast system, the cupola operates with preheating of the combustion air. Temperatures at the cupola exit usually range from 1200 to 2000°F.

2. In the hot blast system, air preheaters preheat the blast air for the cupola. Changes in production rate can be obtained by altering the preheat temperature and air blast volume.

Cupola operation is usually cyclic because of the limited life of the refractory linings. Considerable quantities of effluent, both gaseous and particulate, are evolved, and the amount is seldom constant except for short periods of time. The effluent rate varies with blast rate, coke consumption, physical properties of coke, type and cleanliness of metal scrap in the charge, coke-to-iron ratio, bed height, burden height, and preheat temperature. The effluent rate also changes at intervals when the furnace is charged with iron, steel scrap, coke, and flux.

Stack gases consist mainly of carbon dioxide, carbon monoxide, sulfur dioxide, nitrogen, and oxygen. The sulfur dioxide is probably the most objectionable, both from a standpoint of nuisance odor and as a cause of corrosion to the gas cleaning plant by the formation of sulfurous acid. Carbon monoxide is usually oxidized to carbon dioxide, though explosion can occur if this oxidation is not complete. Among the remaining constituents of cupola waste gas, only fluorine has some occasional importance. The fluorine emission can be attributed to the addition of fluorspar which is sometimes used in basic cupolas to create favorable conditions for desulfurizing by decreasing the slag viscosity. Only a few cupolas are operated with a basic slag.

Particulate material emitted from the cupola stack consists primarily of the oxides of silicon, iron, calcium, aluminum, magnesium, and manganese, but may also contain small amounts of coke dust, coke ash, limestone, zinc oxide, and smoldering products from paint, grease, oil, rubber, and other combustibles. In Table 20 is summarized a mean range of composition of cupola dust as gathered by H. Pacyna from available literature and reported by Engels. Engels also summarizes work by W. Patterson, H. Siepman, and H. Pacyna which gives particulate concentration ranges and scatter values (Table 21).

The particle size distribution ranges between wide limits, depending on melt rate, coke usage, scrap formulation, and furnace operating variables. Older data indicate that the proportion of dust below 10 microns, as a rule, does not exceed 10%, but later studies indicate that particle sizes under 1 μ may constitute 40% and more of the total weight.

There appears to be a relationship between the coke ratio (coke/scrap) and the melting rate per unit area of furnace and the emissions from a cupola stack, as illustrated in Figure 42. While a substantial amount of scatter exists, increasing amounts of coke per unit of iron melted in basic hot blast cupolas generally increase the amount of particulate material. Higher melting rates tend to decrease the amount of particulate when expressed in terms of weight per unit of iron melted. Although the data indicate a wide range of dust emission, most of the data points fall within the range of 4 to 12 lb/t iron.

Particle size distribution data for both hot and cold blast cupolas are presented in Figure 43.

Though the literature search has not revealed extensive utilization of wet precipitators for collection of cupola dusts in the United States, there are a number of such installations overseas, some of the more recent of which are described by Engels and Weber, and Ussleber.[35,36]

One of the first wet-type electrostatic precipitators for dust removal in a hot blast cupola went into operation in early 1964 in a foundry in Velbert, Germany. Figure 44 illustrates the hot blast cupola plant. The comparatively small space available and the fact that a settling tank with pump station was already on hand were decisive in the selection of the wet-type precipitator. The gases not needed in the recuperator are piped directly to the gas

Table 20[34]

CHEMICAL COMPOSITION OF CUPOLA DUST

	Mean Range	Scatter Values
SiO_2	20-40 %	10-45 %
CaO	3-6 %	2-18 %
Al_2O_3	2-4 %	0.5-25 %
MgO	1-3 %	0.5-5 %
FeO (Fe_2O_3,Fe)	12-16 %	5-26 %
MnO	1-2 %	0.5-9 %
Ignition Loss (C, S, CO_2)	20-50%	10-64 %

Table 21[34]

DUST CONTENT OF CUPOLA WASTE GASES

	Main Range	Scatter Values
Cold blast cupola:		
Top gas, undiluted, g/Nm^3	6 - 11	2 - 15
Waste gas from cupola stack, g/Nm^3	2 - 6	1 - 8
Total dust emission, kg/t iron	5 - 10	2 - 12
Hot blast cupola (acid)		
Top gas, undiluted, g/Nm^3	6 - 14	3 - 25
Waste gas from recuperator, g/Nm^3	3 - 7	1 - 10
Residual gas from cupola stack, g/Nm^3	0-5 - 3	0.2 - 7
Total dust emission at cupola furnace, kg/t iron	8 - 12	2 - 20

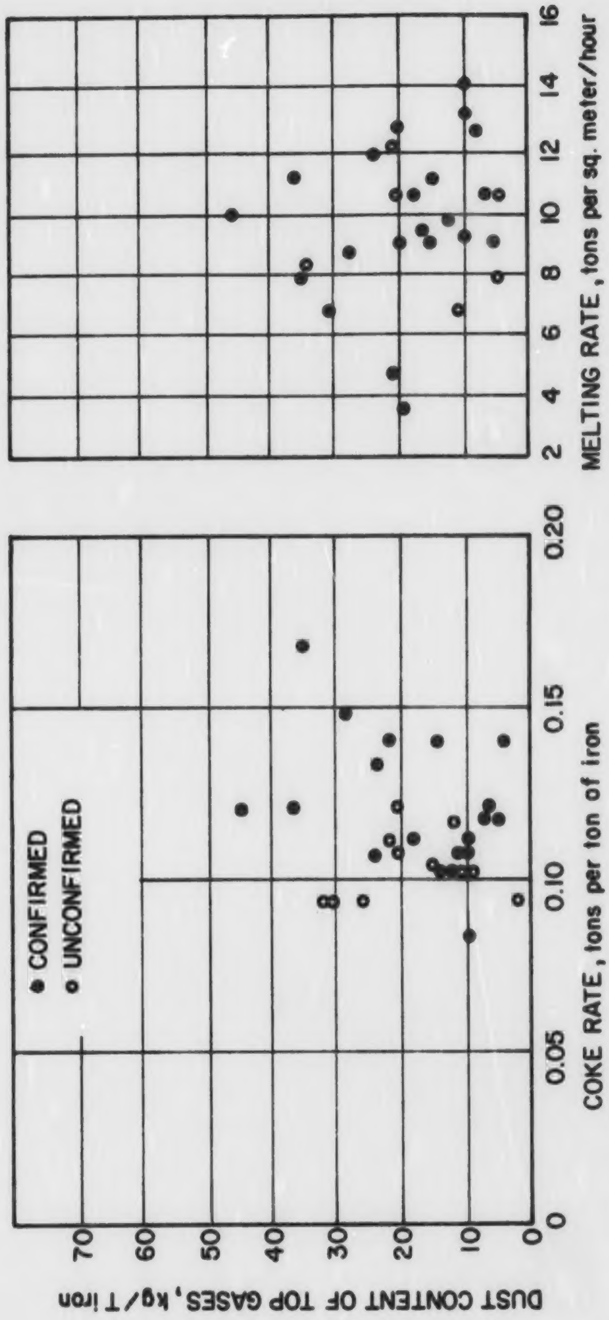


Figure 42. Dust Output Survey as a function of Coke Rate and Melt Rate.[34]

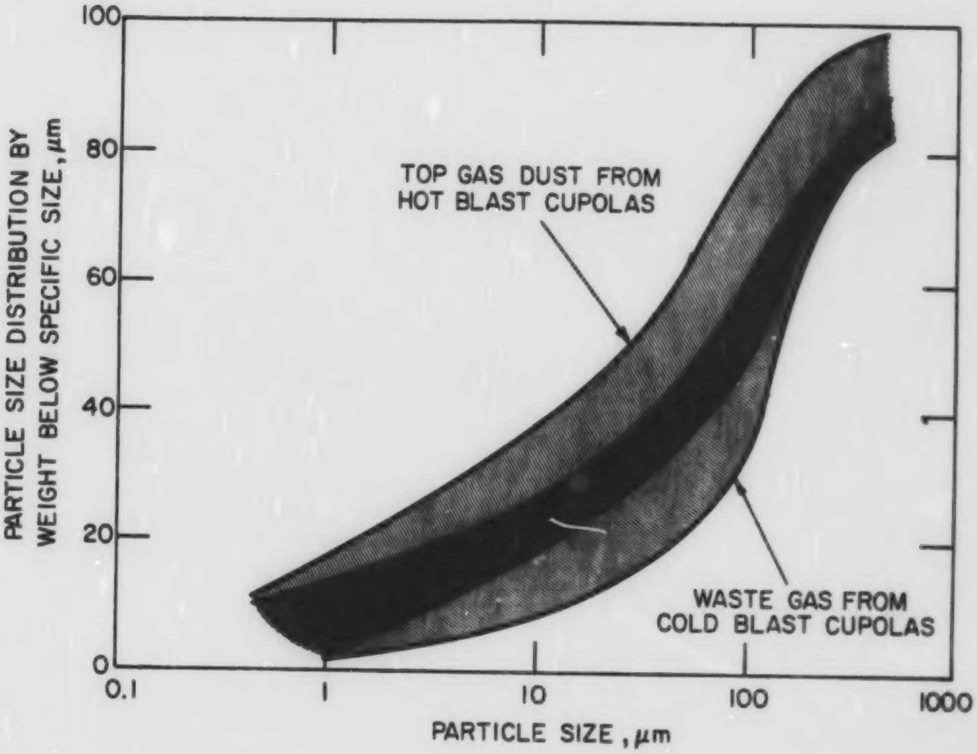
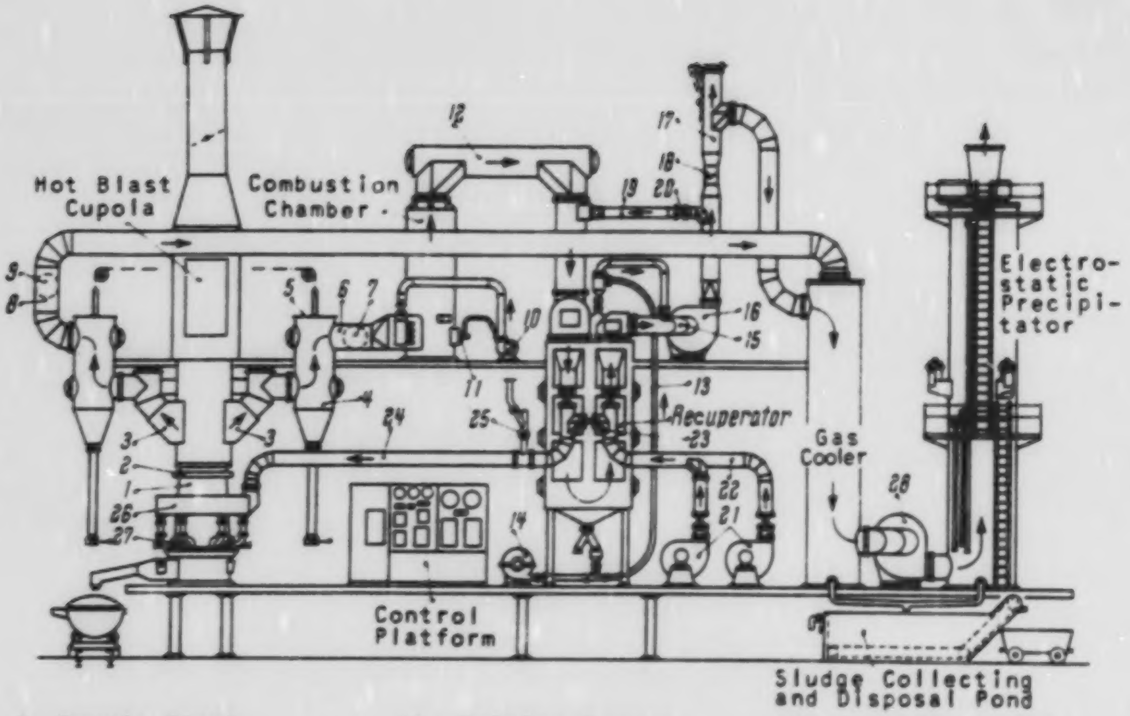


Figure 43. Particle Size Studies Made with Dusts from Hot and Cold Blast Cupolas.[34]


Hot Blast Cupola
Combustion Chamber
Electro-static Precipi-tator
Recuperator
Gas Cooler
Control Platform
Sludge Collecting and Disposal Pond
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

1- Cupola Stack
2- Ring Main for Cooling Cupola
3- Top Gas Offtake
4- Dust Pre-Arrester
5- Gas Stop
6- Gas Main
7- Gas Main From Other Cupolas
8&9- Corresponding Mains For Excess Gas
10- Combustion Air Fan
11- Priming Burner
12- Hot Gas Main
13- Cascade
14- Fan
15- Waste Gas Main
16- Induced Draft Fan
17- Waste-Gas Chimney
18- Chimney Damper
19- Waste Gas Return
20- Butterfly Valve For Waste Gas Return
21- Fresh Air Fan
22- Cold Blast Main
23- Recuperator By-Pass Main
24- Hot Blast Main
25- Blow-Off Valve
26- Bustle Pipe
27- Tuyeres
28- Fan For Dust Extraction

Figure 44. Hot-Blast Cupola Plant (melting rate: 6 m.ton/hr) with Wet Electrostatic Precipitator for Cleaning the Waste Gases.[36]

cleaning plant through a by-pass piping system. The following values were measured:

Dust content of the mixed gas prior to wet precipitator	2.8 g/Nm^3
Clean gas content behind wet precipitator	0.0474 g/Nm^3
Collection efficiency	98.3%
Dust emission	0.384 kg/h = 0.064 kg/t iron

The gas cleaning equipment consists principally of a cooling tower (which cools gases to about 60°C), an induced draft ventilator, the vanes of which are sprayed to prevent scaling, and the vertical wet electrostatic precipitator. Water consumption is 1.5 m^3/h, consumption of neutralizing agent is 16.6 kg/h, and power consumption is 23 KW.

Engels states that the withdrawal of top gases below the top opening is advisable in newly constructed plants where the heat content of the gases is not utilized in the recuperator. The externally-heated hot blast stove is independent of the top gas supply. The top gases are drawn off below the top opening without prior dilution with outside air for cleaning and are first introduced into an Imatra-Venturi scrubber which provides cooling, saturation, and preliminary cleaning. The scrubber is in combination with a vertical wet-type electrostatic precipitator to form an integrated unit. The measured clean gas dust content of 0.084 g/Nm^3 corresponds to a collection efficiency of 98.85%.

A wet precipitator with an Imatra-Venturi scrubber as preliminary filter and saturator is employed for cleaning a mixture of top gas and recuperator waste gas in an acid-lined 12 ton hot blast cupola (Figure 45). In this plant the top gases are completely drawn off below the charge opening, and only part of the gases are introduced into the combustion chamber. With a raw dust content of 4.65 g/Nm^3 and a gas volume of 15,700 Nm^3/h, the system cleans the gases to a dust content of 0.140 g/Nm^3 (97% collection efficiency).

Table 22 presents a cost comparison for various dust collectors for cleaning waste gases of a hot blast cupola. The individual data were taken from various sources and converted by Engels so that costs for the venturi tube dust removal device were fixed at 1 and all other collectors were expressed in relation to the venturi scrubber.

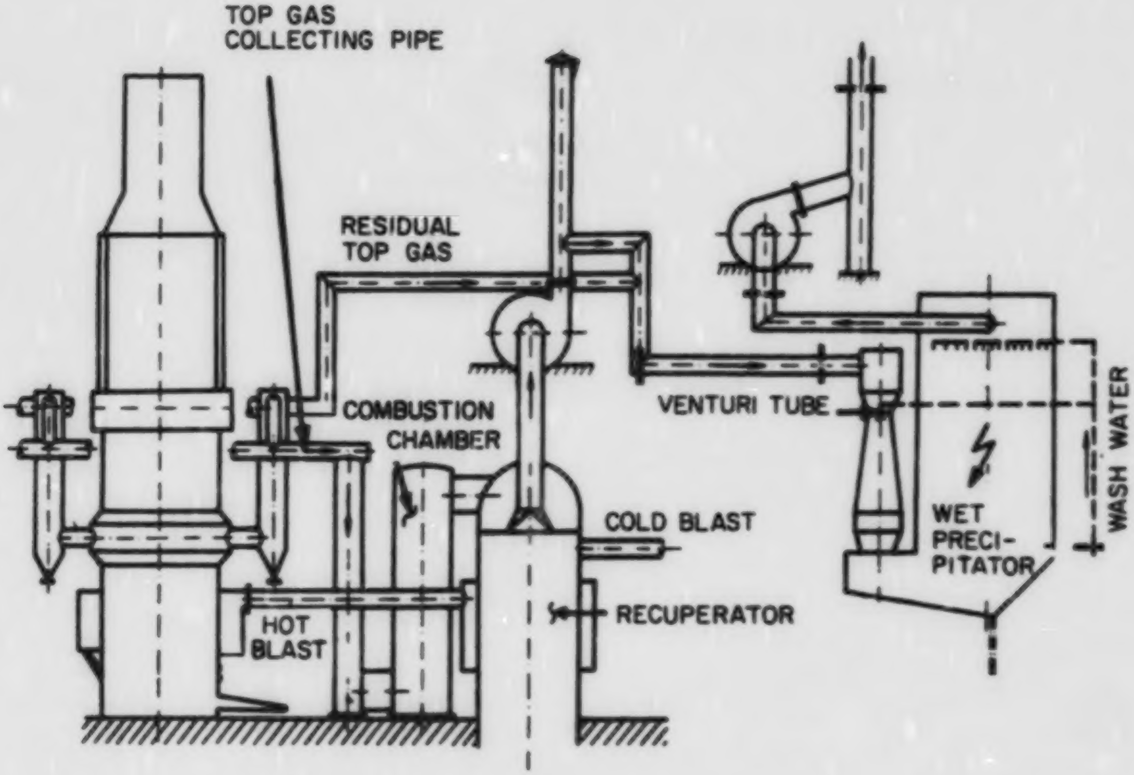

TOP GAS COLLECTING PIPE
RESIDUAL TOP GAS
COMBUSTION CHAMBER
VENTURI TUBE
WASH WATER
WET PRECI-PITATOR
COLD BLAST
RECUPERATOR
HOT BLAST

Figure 45. Waste and Top Gas Cleaning with Wet Electrostatic Precipitator and Venturi in Series.[34]

Table 22.[1*] Cost Comparison for Various Dust Collectors for Cleaning Waste Gases of a Hot Blast Cupola
(Index value 1 for venturi tube dust separation)
Waste gas quantity to be cleaned: 12500 Nm^3/h Depreciation: 20% annum

Plant	Venturi Tube Dust Collector	Wet Dust Collector, Simple Design	Dry Electro-precipitator		Wet Electro-Precipitator	Fabric Dust Collector	
			Offer 1	Offer 2		Offer 1	Offer 2
Guaranteed clean dust content:							
kg/h	3.50	3.50	1.75	2.60	1.75	2.40	1.50
g/Nm^3	0.280	0.280	0.140	0.2	0.140	0.192	0.120
Initial investment costs (Index value)	1.00*	1.04*	3.24	1.68	1.59*	1.45	2.36
Depreciation and interest (Index value)	1.00*	1.04*	3.24	1.68	1.59*	1.45	2.36
Power consumption (Index value)	1.00	0.62	0.23	0.36	0.24	0.65	0.43
Maintenance, servicing, water consumption, neutralization (Index value)	1.00	1.06	0.62	0.536	0.83	0.55	0.54
Costs per operation hour (Index value)	1.00*	0.88*	1.67	1.01	0.96	1.14	1.50

* without facilities for water supply and settling tank

MIST COLLECTION IN THE IRON AND STEEL AND IN THE PETROCHEMICAL INDUSTRY

Electrostatic precipitators are used as collectors of tars and oils in the iron and steel and petrochemical industries. These types of units do not usually employ forced irrigation of the collecting electrodes, but they are "wet" in the sense that the collected material is a fluid, and no rapping is employed. The literature survey has not revealed any significant new developments in this application area since the preparation of "A Manual of Electrostatic Precipitator Technology, Part II" in 1970.[37] Therefore, the following discussion is taken from the Manual and from Research Cottrell reports submitted to SRI under Subcontract No. H-6228.[38,39,63]

The use of mist precipitators is most prevalent in the iron and steel industry for collection of coke oven emissions. Coke, the chief fuel used in blast furnaces, is the residue after distillation of certain grades of bituminous coal. The two methods of producing metallurgical coke are the beehive and by-product processes. The beehive process was used for coke production in the U.S. until about 1917, and since there were just a few beehive oven installations where the waste heat from the products of combustion was used in steam generating units, no attempts at gas cleaning were made. The by-product process is presently used in the production of 98% of all coke, primarily because of its favorable economic aspects. Gas cleaning equipment is necessary in the by-product process since means are provided for full utilization and recovery of the gas and coal chemicals. In short, all the products of combustion and destructive distillation of the coal involved in the beehive process are vented directly to the atmosphere while those of the by-product process are withdrawn from the oven and processed to produce useful by-products. A coke oven flow diagram is shown in Figure 46.

In either type of oven, the beehive or by-product, the coke producing processing consists mainly of driving off certain volatile matter, leaving in the residue a high percentage of carbon mixed with relatively small amounts of impurities. The beehive oven, seldom used anymore, will not be discussed in this report. In the by-product coking process, the coal is heated in the absence of air, and the volatile material is piped to equipment which extracts the valuable ingredients. After the extraction process, some of the gas (heating value, 550 Btu/ft^3) returns to the ovens for use in heating the coking chambers and other plant processes. These ovens are rectangular in shape, usually 30 to 40 feet long, 6 to 14 feet high, and 11 to 22 inches wide. As many as 100 of them may be set together in a battery for ease in charging

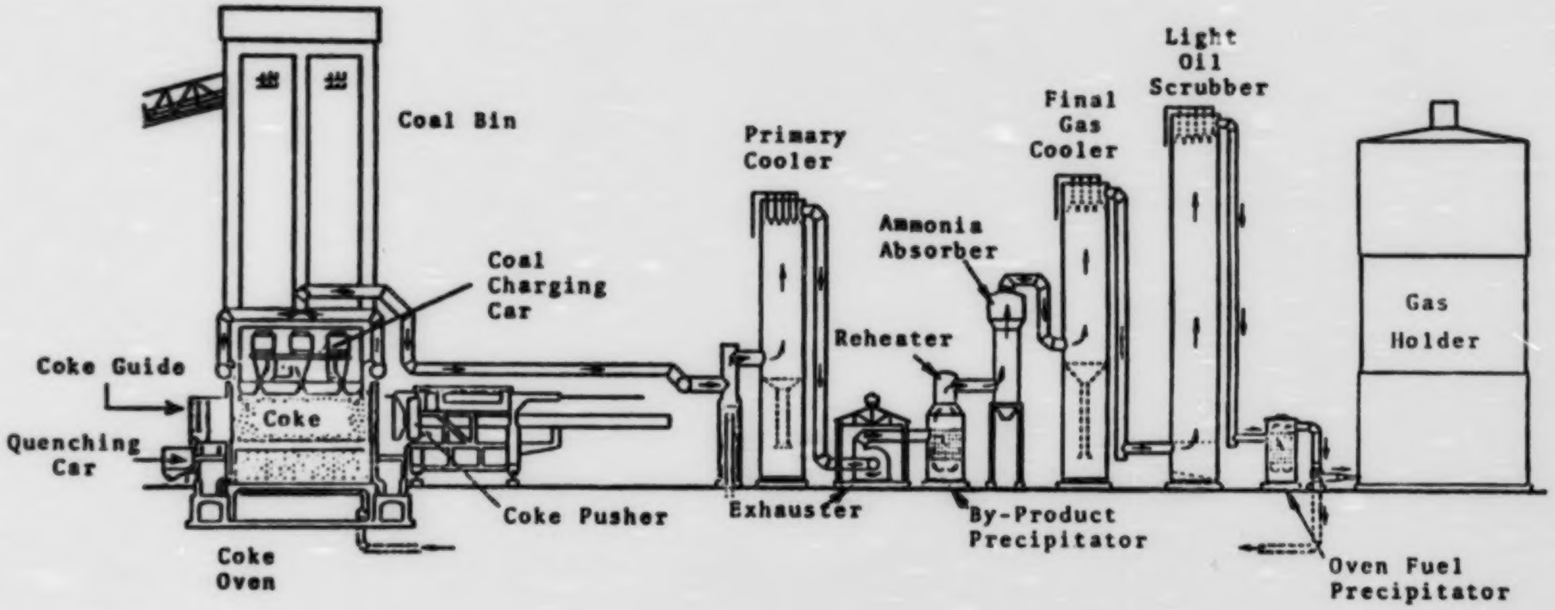

Coal Bin
Coal
Charging
Car
Coke Guide
Coke
Quenching
Car
Coke
Oven
Coke Pusher
Primary
Cooler
Exhauster
Reheater
Ammonia
Absorber
By-Product
Precipitator
Final
Gas
Cooler
Light
Oil
Scrubber
Oven Fuel
Precipitator
Gas
Holder

Figure 46. Coke Oven Flow Diagram[38]

and discharging the coal and coke. Ports at the top of the oven can receive 16 to 20 tons of coal. The ports are then sealed and coal begins to fuse, starting at the walls of the oven, which may generate heat from 1600° to 2100°F. When coking is finished (18 to 20 hours), doors at the ends of the oven chamber are opened, and a pusher ram shoves the entire charge of the coke into railway cars.

As stated above, the products of destructive distillation in the by-product process are withdrawn from the oven and processed to produce useful by-products. Carbonization of one one of coal yields the following products:

coke	1200-1400 lbs
coke breeze	100-200 lbs
coke oven gas (550 Btu/cf)	9500-11,500 cf
crude light oil	2-4 gallons
tar	8-12 gallons
ammonium sulfate	20-28 lbs
ammoniacal sulfate	13-35 gallons

All of the above products except the coke leave the oven in association with the gas. The analysis of the gas coming from the coke is approximately as follows:

CO_2	2.2%
O_2	0.8%
N_2	8.1%
CO	6.3%
H_2	46.5%
CH_4	32.1%
C_2H_4	3.5%
C_6H_6	0.5%

The concentration of suspended matter at the precipitator inlet varies from 1 to 15 grains/scf. Water comprises about 50% of total precipitate, the remainder being tar, oil, etc.

Control Technology

As early as 1916 pilot scale electrostatic precipitators were demonstrating the technical feasibility of removing tar from coke oven gas, but fear of explosions caused by sparking caused reluctance on the part of industry. Successful operation eventually eliminated resistance, and in 1927 commercial installations in coke oven gas were first made and rapidly became standard equipment. The arrangement of equipment developed to remove and recover coke oven emissions is shown in Figure 46. The gas leaves the ovens at 1100 to 1300°F, after which it is cooled to about 95°F, thus condensing out a considerable amount of tar and ammoniacal liquor. These condensed products are processed further in other equipment for separation and refinement. The gas then passes through the exhauster and enters the electrostatic precipitator where the suspended oil and tar are collected with an efficiency normally between 95 and 99%. The gas then moves through reheaters, ammonia absorbers or saturators, gas coolers, and light oil scrubbers, before entering the gas holder. If the gas is to be used for underfiring the coke ovens, the gas must be further cleaned in another electrostatic precipitator referred to as a fuel gas precipitator, which cleans the gas sufficiently to prevent the deposition of tar in the very small apertures of the coke oven burners. Some of this gas is also used to ventilate the insulator compartments of the primary precipitator. The gas volume used for underfiring is usually a small fraction of the total gas, and consequently, only relatively small precipitators are required.

The typical electrostatic precipitator used for detarring consists of a group of grounded pipes six inches to eight inches in diameter and six feet to nine feet in length, suspended from a header plate in a round shell. Figure 47 shows the typical design for this type precipitator. The early coke oven precipitators were energized by electrical equipment using mechanical rectifiers, thus requiring a separate substation to house the electrical controls, transformers, and rectifiers. The more recent utilization of tube and silicon rectifiers permits the location of the rectifiers and transformers in weatherproof cabinets, thereby eliminating the necessity for substations. Figure 48 shows a self-contained tar precipitator attached to the shell of which is a compartment containing a 35 kV electrical set with tube rectifier. The collecting pipes of this unit are six inches in diameter and six feet long.

Another precipitator design used for cleaning coke oven gas is shown in Figure 49. The discharge electrode wires are centrally located in the annulus between the concentric tube-collection electrodes. Both surfaces of the tubes serve as collecting surface.

Based on data from a group of installations covering a period of 1931 to 1961, design efficiencies are generally about 95-99%. Typical design parameters for coke oven gas precipitators are given in Table 23.

TABLE 23[38]

TYPICAL COKE OVEN GAS PRECIPITATOR DESIGN PARAMETERS

148 pipes, 8 in. dia. x 9 ft. long

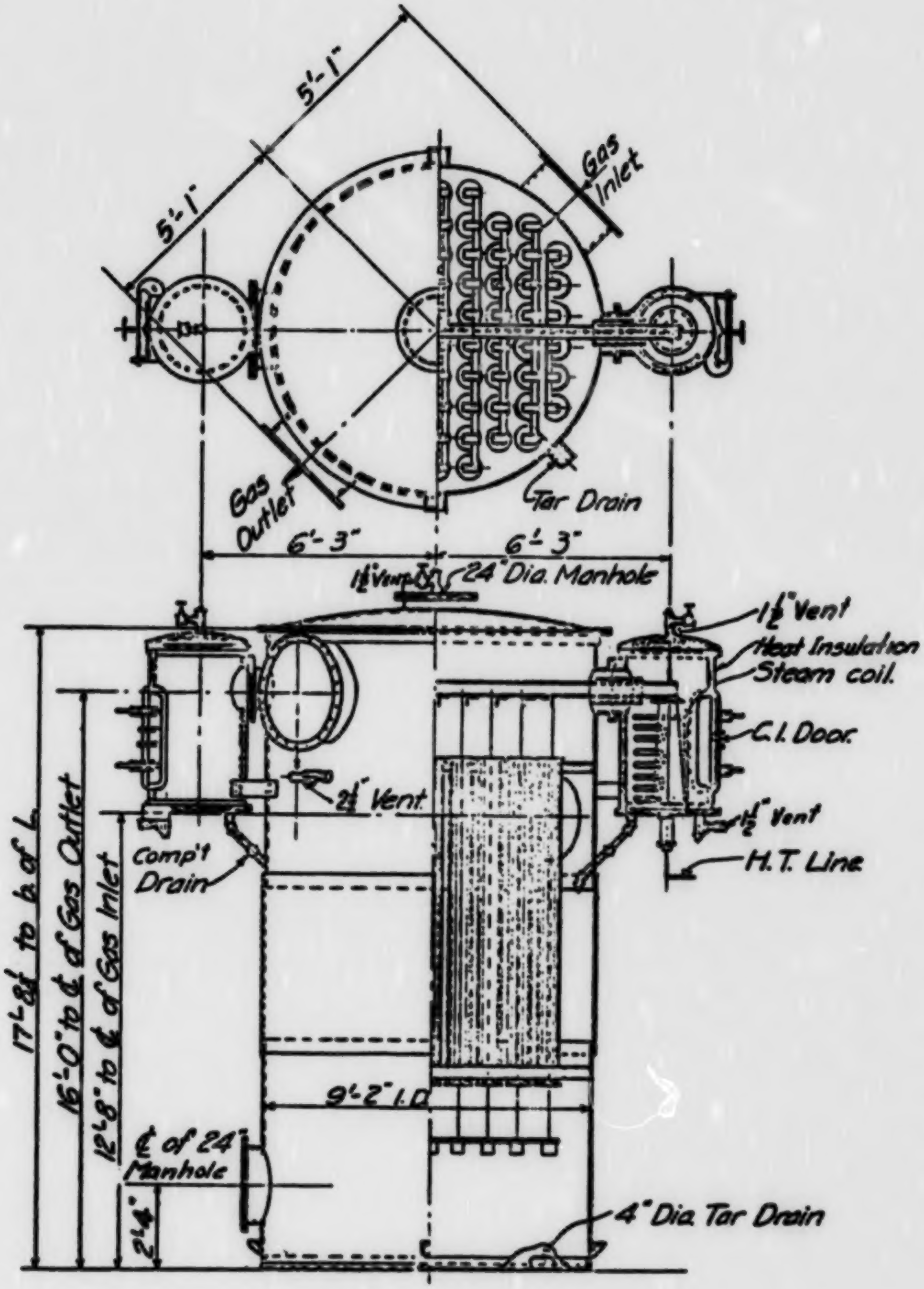

5'-1"
5'-1"
5'-1"
Gas Inlet
Gas Outlet
Tar Drain
6'-3"
6'-3"
1½" Vent
24" Dia. Manhole
1½" Vent
Heat Insulation
Steam coil.
C.I. Door.
2½" Vent.
1½" Vent
H.T. Line
Comp't Drain
17'-8¼" to b. of L
16'-0" to ℄ of Gas Outlet
12'-8" to ℄ of Gas Inlet
9'-2" I.D.
℄ of 24" Manhole
2'-4"
4" Dia. Tar Drain

Figure 47. Typical Pipe Type Electrostatic Precipitator for Collection of Tar.[38]

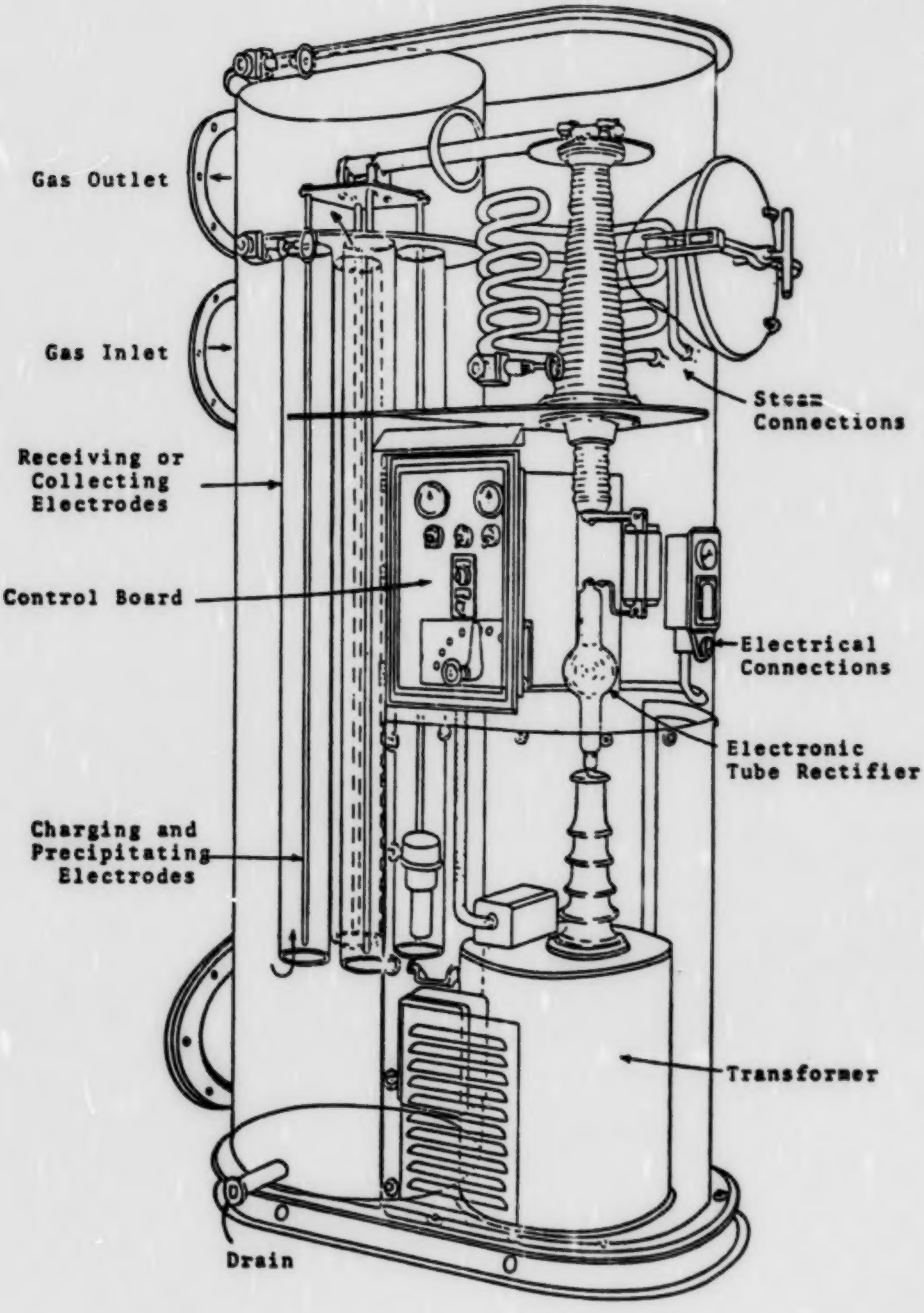

Gas Outlet
Gas Inlet
Steam Connections
Receiving or Collecting Electrodes
Control Board
Electrical Connections
Electronic Tube Rectifier
Charging and Precipitating Electrodes
Transformer
Drain

Figure 48. An Integral Tar Collecting Pipe Type Precipitator.[38]

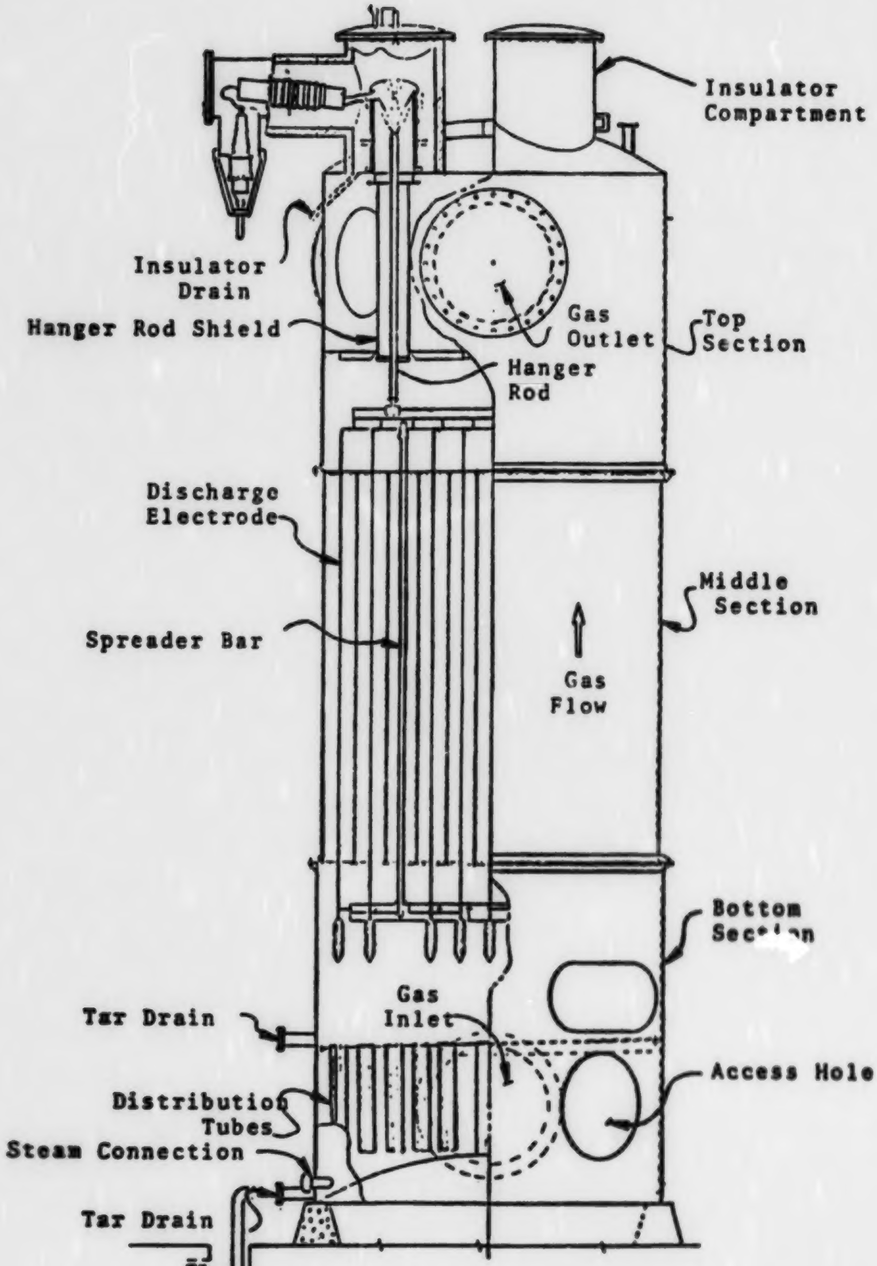

Insulator Compartment
Insulator Drain
Hanger Rod Shield
Gas Outlet
Top Section
Hanger Rod
Discharge Electrode
Middle Section
Spreader Bar
Gas Flow
Bottom Section
Gas Inlet
Tar Drain
Access Hole
Distribution Tubes
Steam Connection
Tar Drain

Figure 49. Concentric Ring Detarrer[38]

Gas flow = 16,500 cfm at 100°F
Inlet concentration = 0.68 gr/cf
Outlet concentration = 0.0068 gr/cf
Efficiency = 99%
Precipitation rate parameter = 13.7 cm/sec
Corona power = 190 watts/1000 cfm

Table 24 gives an average of electrostatic precipitator design parameters for detarring coke ovens. The ratio (R) is the ratio of performance to design precipitation rate parameters.

TABLE 24[38]

AVERAGE DESIGN PARAMETERS FOR COKE OVEN PRECIPITATORS

No. of Installations	Avg. Gas Vel.(Ft/sec)	Avg. Ppt. Field Strength (kV/in.)	Avg. Ppt. Input Power (watts/1000 cfm)	Avg. Ppt. Gas Temp, °F	Avg. Ppt. Inlet Loading (gr/scfd)	Average Ratio (R)
12	8.3	11.2	100	113	0.3	1.11

Average precipitator cost data both on an FOB and erected basis are presented in terms of cost per ACFM for the efficiency and gas volume indicated in Table 25. Numbers in parentheses are numbers of installations used in determining the costs indicated.

TABLE 25[38]

PRECIPITATOR ECONOMICS FOR DETARRING OF COKE OVEN GAS
(Time Period 1959-1969)

Type Precipitator	Gas Volume Range - 100's ACFM	Eff. Range - %	Avg. Cost in Dollars/ACFM Erected	FOB
Pipe-type	0-50	95	3.55(2)	2.52(3)
(vertical flow)	50-100	95	1.43(1)	1.10(1)

Because of the limited number of installations, the above data is only a rough indication of costs.

Detarring in the petrochemical industry is primarily concerned with the cleaning of water gas, oil gas, and producer gas. As in the case of tar removal from coke oven gas, the precipitation of tars from the gases of the petroleum industry is technically straightforward inasmuch as the precipitated tars are usually free flowing.

A relatively new application is the use of electrostatic precipitators to remove tar, fine carbon, and oil mist from the acetylene gas manufactured from naphtha or crude oil. Another relatively new application in the petrochemical field is the utilization of precipitators for the removal of tars from oil shale distillation gases. This application may become more important with the recent acceleration of oil production from shale. The purpose of the precipitator in this application is to clean the gases which are subsequently condensed and treated to produce petrochemical products.

In the process for manufacturing carburetted water or producer gas, the initial gas known as "blue gas" is made by passing steam through a bed of incandescent carbon, which may originate from either coke or anthracite coal. There are two cycles, designated in plant parlance as "make" and "blow". The coal or coke is fed to the gas generator and air is admitted under the bed during the "blow" cycle. The air is shut off and steam is admitted for the "make" cycle. The residue ash is then withdrawn. Carburetted blue gas is a mixture of blue gas (or water gas, as it is often termed), made as above, and oil gas formed by the cracking of oil in a chamber through which the blue gas passes.

The carburetting process enriches the blue gas to as much as 700 Btu per cubic foot of gas, depending upon the amount of oil used. With the present day use of natural gas, many companies mix natural gas with the above gases, the mixture being automatically controlled by means of calorimetric equipment. Prior to entering the precipitator the gas is passed through a direct contact water cooler where the temperature is reduced to around 100°F and saturated with water vapor. In the cooler some of the tars and oils contained in the gas are scrubbed out by the water sprays, and sulfur compounds and other gaseous material are removed from the system in purifiers located after the electrostatic precipitator. A process flow diagram of production of carburetted water gas is shown in Figure 50.

The process for separating oil from shale is shown in the flow diagram, Figure 51. The shale to be processed is fed into a retort where heat is applied to drive off the various components such as gas, oil, and carbonaceous residue. From the retort the gas is passed through indirect water coolers where most of the condensable material condenses out as a submicron sized mist. The mist-laden gas in then introduced to the precipitator where the condensed oil and carbonaceous residue are separated from the gas.

Natural gas is used as the primary raw material in the production of acetylene. The gas is burned in an oxygen-limited atmosphere under controlled temperature and pressure. The gaseous products consist of from 50 to 55% hydrogen, from 30 to 35% carbon monoxide, and from 7 to 9% acetylene. Because of the explosion hazards involved, the oxygen content is rigidly controlled to a fraction of 1%. In addition to the gases, submicron size particulate carbon is also produced and carried along by the gas as a smoke. Prior to entering the precipitator, the gas is passed through a direct-contact water cooler where the temperature is reduced to about 100°F. The gas then enters the wet-type precipitators where practically all of the remaining carbon is removed from the gas.

The Cottrell precipitator for detarring manufactured gases was first developed at the plant of the Ann Arbor Gas Company at Ann Arbor, Michigan, about 1914, while the first commercial application recorded was on producer gas in 1916 at the Minnesota Steel Company at Duluth, Minnesota.[40] In initial applications the gas was usually treated following the wash boxes or scrubbers at low temperature, so that the tar was collected in the presence of water. Early experimental and semi-commercial operations soon led to regular commercial installations. In 1924 there were five such installations in the United States cleaning about 70 million cubic feet per day. By 1962 there were 600 tar precipitators treating 5 million cfm of fuel gas. Since 1962 only about 25 additional tar precipitators have been installed with some of these being replacements for old precipitators.

The electrostatic precipitator most commonly utilized for detarring and cleaning of gaseous products is a single-stage vertical wire and pipe unit, as illustrated in Figure 52. A plate type unit is shown in Figure 53.[41]

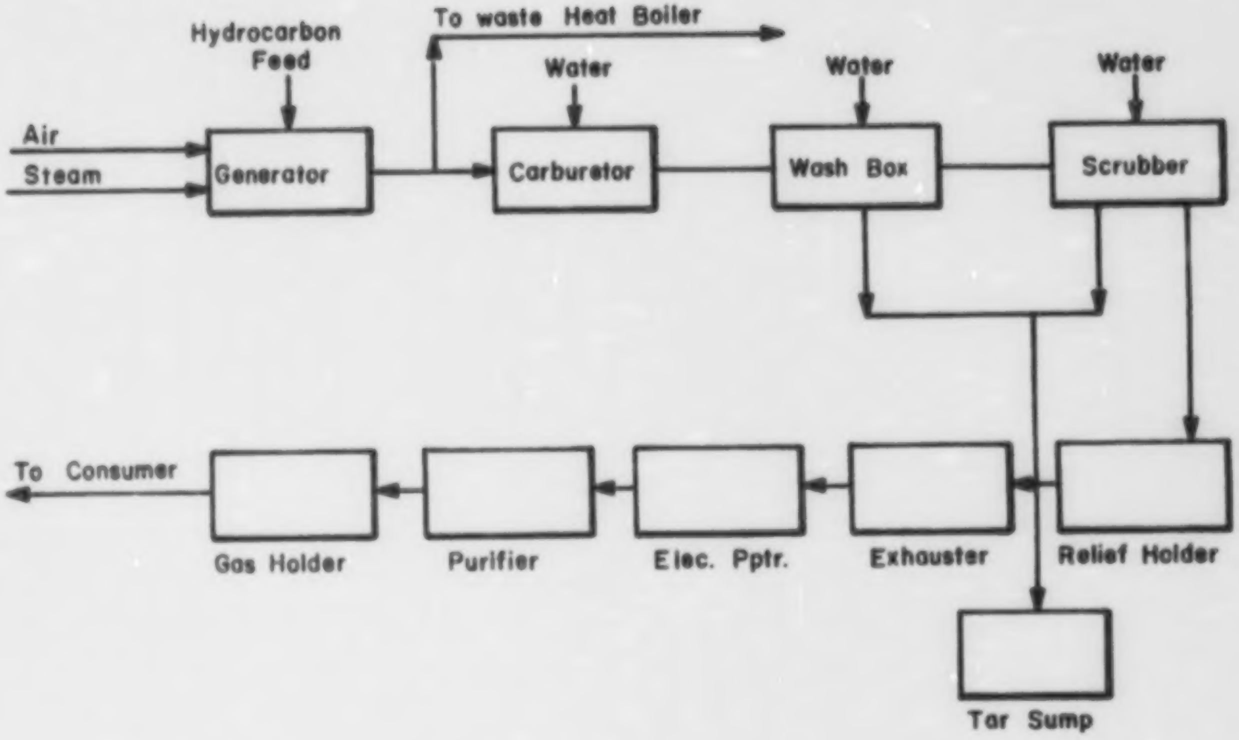

Hydrocarbon Feed
To waste Heat Boiler
Water
Water
Water
Air
Steam
Generator
Carburetor
Wash Box
Scrubber
To Consumer
Gas Holder
Purifier
Elec. Pptr.
Exhauster
Relief Holder
Tar Sump

Figure 50. A Process Flow Diagram of Production of Carburetted Water Gas[63]

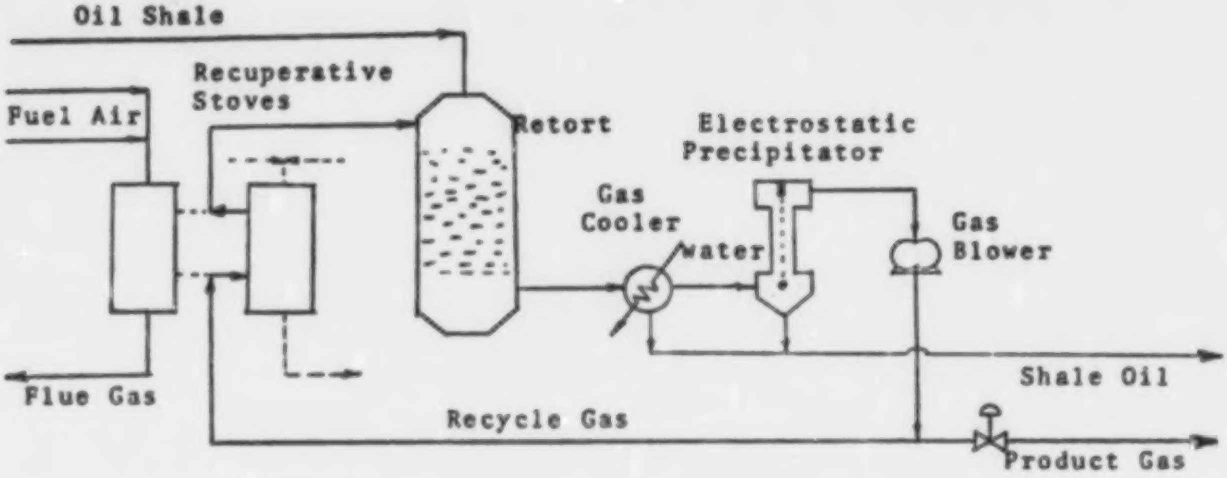

Oil Shale
Recuperative Stoves
Fuel Air
Retort
Electrostatic Precipitator
Gas Cooler
Water
Gas Blower
Flue Gas
Shale Oil
Recycle Gas
Product Gas

Figure 51. Oil Shale Retorting Process[63]

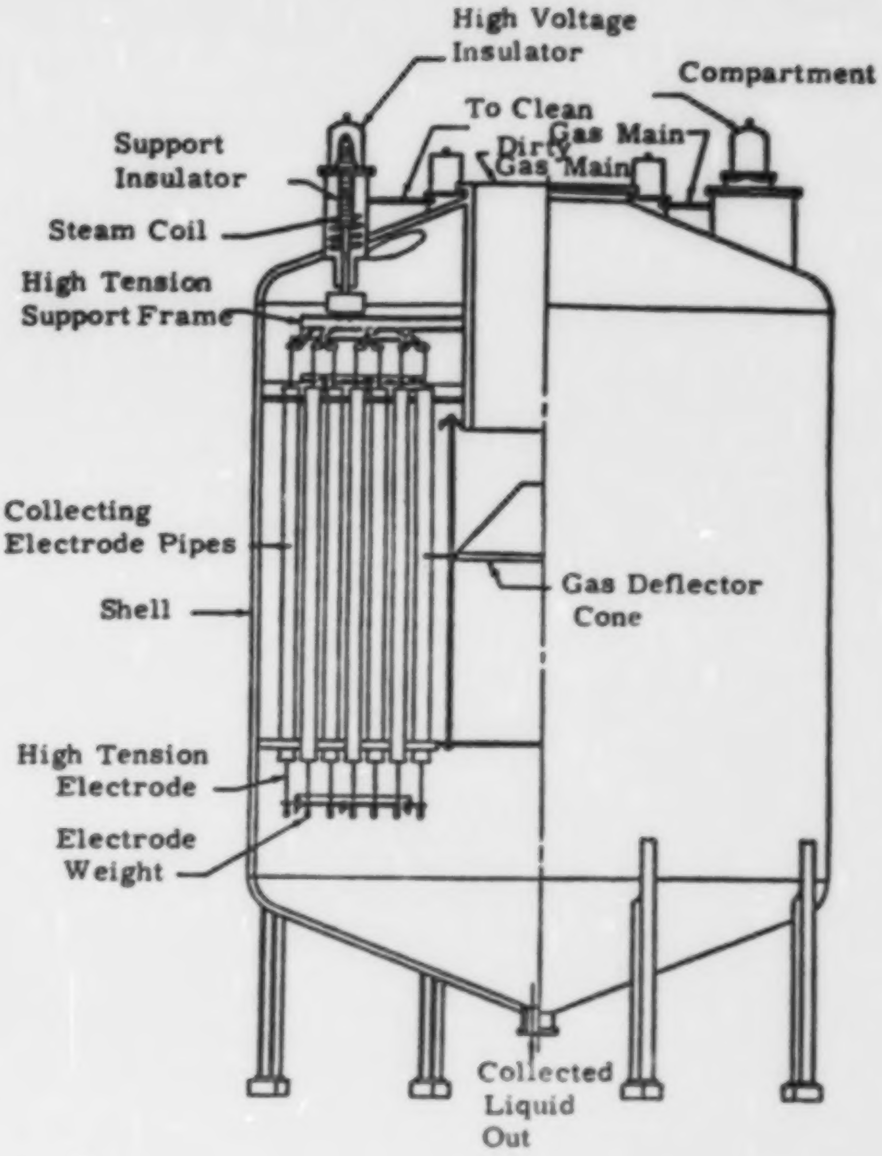
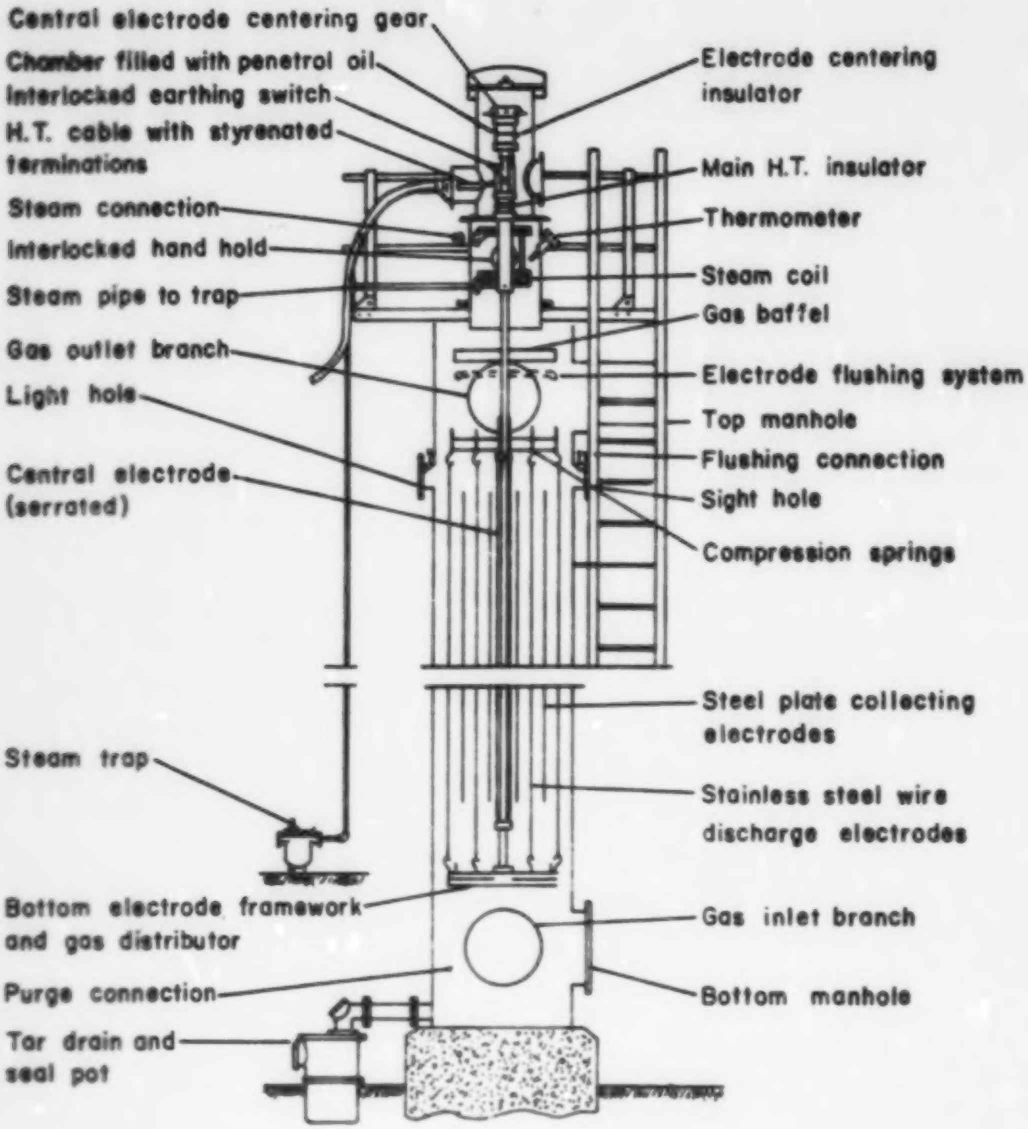

High Voltage Insulator
Compartment
To Clean Gas Main
Dirty Gas Main
Support Insulator
Steam Coil
High Tension Support Frame
Collecting Electrode Pipes
Shell
Gas Deflector Cone
High Tension Electrode
Electrode Weight
Collected Liquid Out

Figure 52. A Single-Stage Vertical Wire and Pipe Unit[38]



Central electrode centering gear
Chamber filled with penetrol oil
Interlocked earthing switch
H.T. cable with styrenated terminations
Steam connection
Interlocked hand hold
Steam pipe to trap
Gas outlet branch
Light hole
Central electrode (serrated)
Steam trap
Bottom electrode framework and gas distributor
Purge connection
Tar drain and seal pot
Electrode centering insulator
Main H.T. insulator
Thermometer
Steam coil
Gas baffel
Electrode flushing system
Top manhole
Flushing connection
Sight hole
Compression springs
Steel plate collecting electrodes
Stainless steel wire discharge electrodes
Gas inlet branch
Bottom manhole

Figure 53. Plate-Type Precipitator Used for Detarring[41]

The precipitator universally used for the removal of tars and oils from carburetted water gas is a single stage vertical pipe type unit. The design consists of the collecting pipes, supported from a top header and immersed in the incoming gas. The high voltage support insulators are mounted in heated turrets attached to the side of the unit, which is cylindrical in shape. The precipitator is provided with gas purge connections at all of the high points in the system. This type of unit is often referred to as a "low-volume tar" precipitator. The discharge electrode used in the low-volume tar precipitator is known as the "stiff rod and prong" electrode. The most widely used form of this type electrode consists of pointed star-shaped washers spaced about 1 1/2 inches apart along a rigid rod for its full length. Collecting electrodes are of the pipe type, the sizes of which vary from 6" to 15" diameter. The discharge electrode assembly is supported directly on the insulators which are mounted on brackets inside of the precipitator directly in the gas stream.

The collected tars and oil are free flowing and are removed from the vessel sump to an external tar pot through a liquid trap. From the tar pot the liquid is pumped to its final point of reuse or disposal.

The precipitator most commonly used for cleaning acetylene gas is a single-stage, vertical flow type unit. To withstand the gas pressure the configuration of the shell is cylindrical. The collecting pipes are supported from a top header. The outer surfaces of the collecting pipes are exposed to the incoming gas, while the inside surfaces are continuously flushed by a film of water which overflows weirs attached to the top of the pipe. The normal overflow is augmented by periodic spraying from sprays located under the roof.

Customarily there is only one type of discharge electrode used in the treatment of acetylene gas, the "weighted twisted squares" or weighted bar electrodes. These electrodes consist of vertically hung square bars spanning the full height of the collecting electrodes. They are usually 3/16" or 1/4" square and are twisted longitudinally, held by weights at the bottom. Because of the moisture content of the gas treated in the precipitator, the discharge electrode support system consists of heated outboard compartments. In this arrangement the discharge electrode frame is supported by a horizontal beam running across the top of the precipitator. The beam is supported by two insulators, one on either side, located in heated compartments attached to the outside of the precipitator shell.

The precipitator used to collect the oil and carbonaceous material from shale oil manufacture consists of a single stage vertical flow unit using pipes for the collecting surface. The vessel construction is cylindrical. Since the temperature of the gas being treated approaches atmospheric, no thermal insulation is used. The collected liquid accumulates in a sump provided at the bottom of the shell. The discharge electrodes for shale oil application are of the weighted wire and stiff rod and prong types, and the support frame used is the heated outboard compartments method. The use of pipe type collecting electrodes is common for the small sized precipitators normally used in shale oil production.

Table 26 presents a summary of design data for electrostatic precipitator installations in fuel gas purification from 1940 to 1963.

COLLECTION OF ACID MISTS FROM SULFURIC AND PHOSPHORIC ACID PRODUCTION

Sulfuric Acid Production

Basically, the production of sulfuric acid involves the oxidation of generated sulfur dioxide to sulfur trioxide and its hydration to sulfuric acid. Sulfuric acid capacity in 1970 amounted to 38 million short tons produced in 250 plants of which 215 are of the contact type, the remaining 35 being the older chamber type.

The chamber process uses the reduction of NO_2 to NO as the oxidizing mechanism to convert the SO_2 to SO_3. The oxidation takes place in lead-lined chambers. However, the process produces sulfuric acid with a concentration of only about 78% and this low concentration together with high operational costs and NO_x emissions, have caused an ever diminishing use of the chamber process. For these reasons, this discussion will deal exclusively with the contact process of sulfuric acid manufacture.

The chemistry of the contact process is very simple. First, the sulfur in the feedstock is burned in air, giving sulfur dioxide:

$$S + O_2 \rightarrow SO_2$$

Then the sulfur dioxide is catalytically oxidized to sulfur trioxide:

$$2SO_2 + O_2 \rightarrow 2SO_3$$

TABLE 26[63]

A SUMMARY OF DESIGN DATA OF ELECTROSTATIC PRECIPITATORS ON VARIOUS APPLICATIONS FOR REMOVING TAR AND OIL MIST OVER PERIOD 1940 to 1963

Type of Applications	No. of Install.	Suspended Matter	Total Gas Vol. ACFM	Temperature °F	Collecting Efficiency %
Carburetted Water Gas	55	Tar and Oil Mist	315,800	70-110	95
Oil Gas	3	Tar and Oil Mist	18,200	80-100	95-98
Reformed Gas	3	Tar and Oil Mist	3,200	80-100	95-98.5
Shale Oil Gas	2	Tar and Oil Mist	20,900	100-200	95-97.5
Acetylene	1	Tar and Oil Mist	42,100	100	99-92

Finally, the sulfur trioxide is absorbed in a strong, aqueous solution of sulfuric acid:

$$SO_3 + H_2O \rightarrow H_2SO_4$$

Contact plants are often classified according to the raw materials charged to them; e.g., elemental sulfur, spent acid, and hydrogen sulfide, and sulfide ores and smelter gas. The sulfur burning plants are sometimes called hot-gas purification plants, while those plants which utilize sulfide ores are called metallurgical or cold gas purification acid plants. Plants burning hydrogen sulfide may be of the hot-gas or true wet-gas purification type, the latter case being where the sulfur dioxide gas is not dried, thus allowing the moisture to pass through the conversion system.

Sulfur burning plants require no gas purification (except for hot filtration) and are the most inexpensive of the contact type plants. No heat is required for the SO_2 gases, only cooling, so that all heat evolved may be recovered as relatively high pressure steam. A flow chart for this system is shown in Figure 54, and can be divided into the following sequences:[42]

Transportion of sulfur to the plant

Melting of sulfur

Pumping and atomizing of melted sulfur

Burning of sulfur

Recovery of heat from or cooling of hot SO_2 gas

Purification of SO_2 gas (by hot filtration)

Oxidation of SO_2 to SO_3 in converters

Temperature control to secure good yields of SO_3

Absorption of SO_3 in strong acid

Cooling of acid from absorbers

Pumping of acid over absorption towers

Two types of plants are used to process sulfuric acid produced by burning hydrogen sulfide and spent-acid. In one, the sulfur dioxide and the combustion products are passed through gas-cleaning and mist removal equipment. Mist removal is usually accomplished by electrostatic precipitation and moisture removal by absorption in concentrated sulfuric acid. The gas stream then passes through

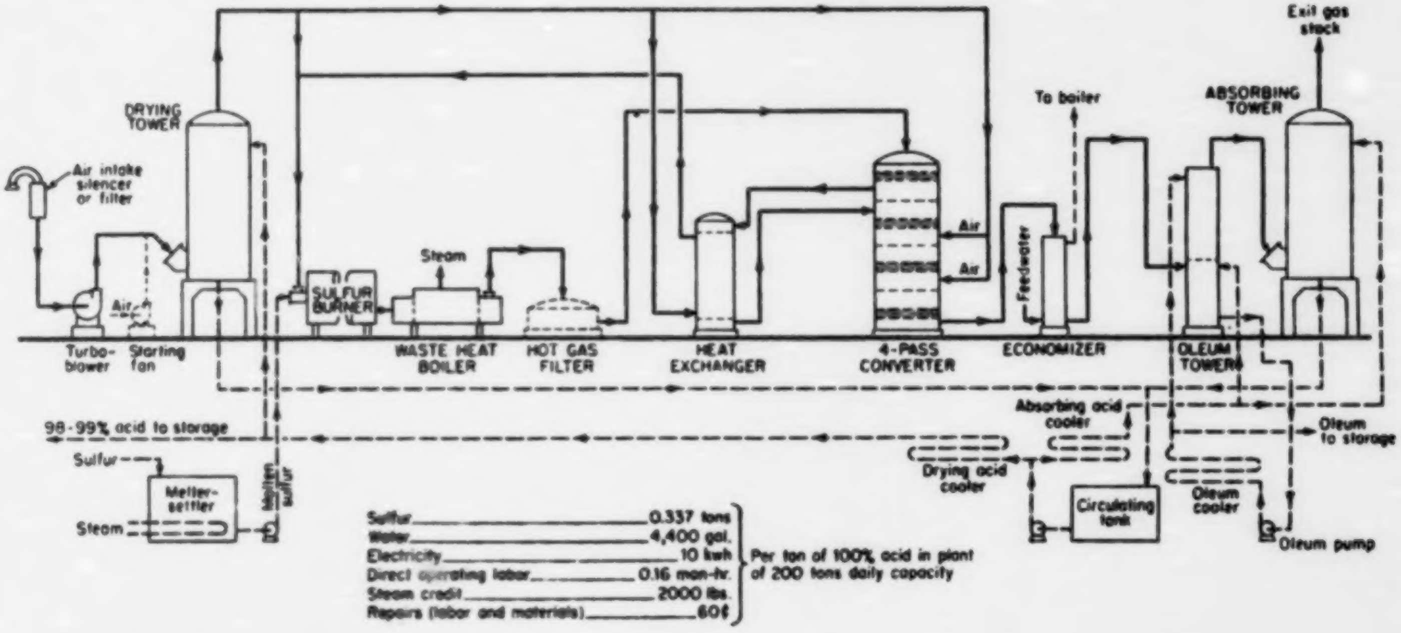

Exit gas stack
ABSORBING TOWER
To boiler
DRYING TOWER
Air intake silencer or filter
Steam
Air
Air
Air
Feedwater
SULFUR BURNER
Turbo-blower
Starting fan
WASTE HEAT BOILER
HOT GAS FILTER
HEAT EXCHANGER
4-PASS CONVERTER
ECONOMIZER
OLEUM TOWERS
Absorbing acid cooler
98-99% acid to storage
Oleum to storage
Sulfur
Melter-settler
Molten sulfur
Steam
Drying acid cooler
Circulating tank
Oleum cooler
Oleum pump
Sulfur 0.337 tons
Water 4,400 gal.
Electricity 10 kwh
Direct operating labor 0.16 man-hr.
Steam credit 2000 lbs.
Repairs (labor and materials) 60¢
Per ton of 100% acid in plant of 200 tons daily capacity

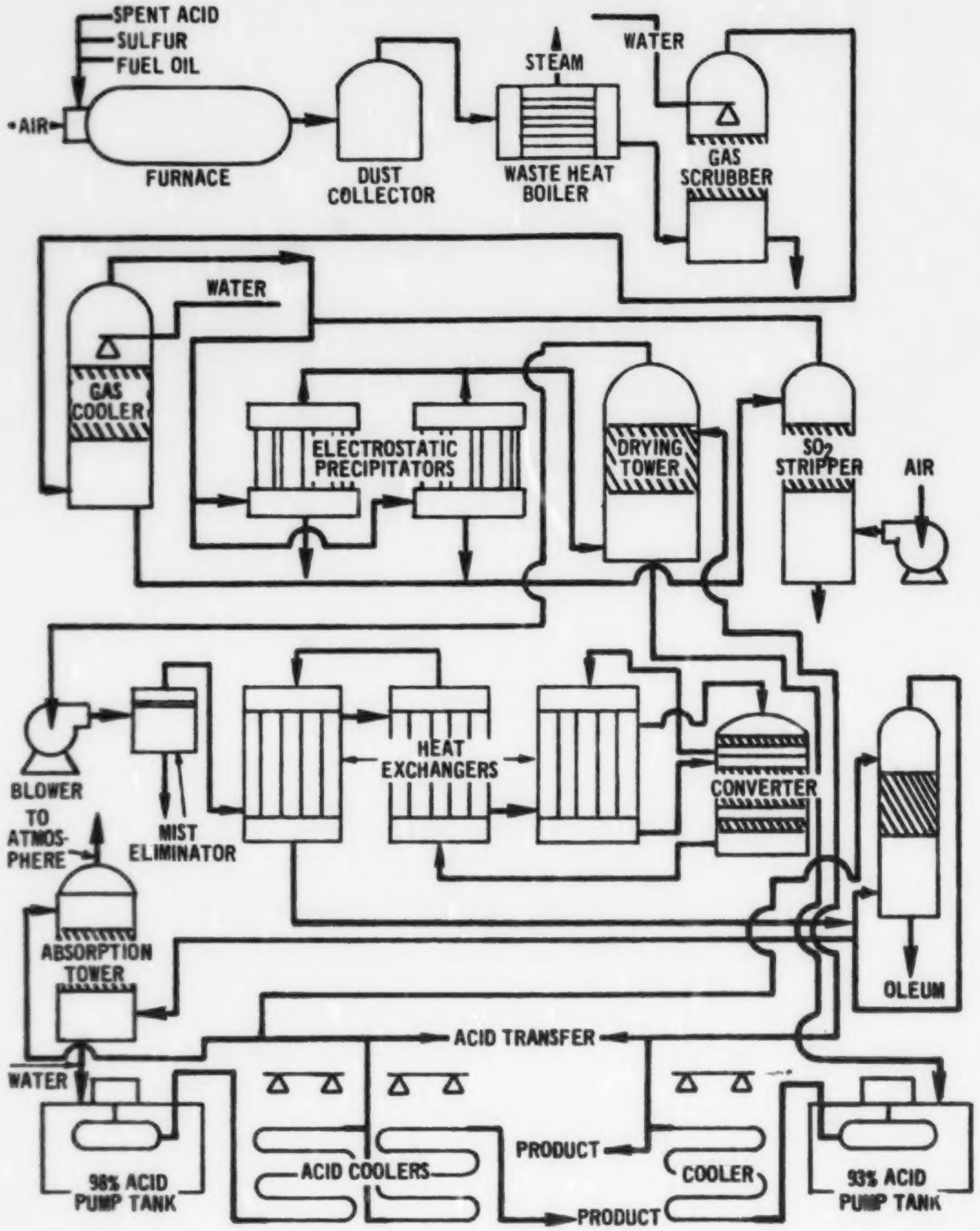
Figure 54. Typical flowchart for sulfur-burning contact plant.[42]

a drying tower from which a blower draws the gas and discharges it to the sulfur trioxide converter. A schematic of the contact process sulfuric acid plant burning spent acid is shown in Figure 55.[43] In the other type plant, known as a "wet-gas plant", the wet gases from the combustion process are charged directly into the converter after heat recovery with no intermediate treatment. A highly efficient mist recovery system following the absorber is required since absorption is not highly efficient due to the excess moisture and acid mist content of the gas.

The configuration of sulfide ore and smelter gas plants is very similar to that of a spent-acid plant except that a roaster is used in place of the combustion furnace. The raw material used in these plants is smelter gas available from ore roasting, smelting, and refining operations associated with nonferrous metals production. The sulfur dioxide in the gas is contaminated with dust, acid mist, and gaseous impurities, the removal of which is accomplished by cyclone dust collectors, scrubbers and electrostatic precipitators (wet, dry, or mist type). After the gases are cooled and cleaned and the excess water vapor removed, they are scrubbed with 98 percent acid in a drying tower. Beginning with the drying tower stage, the process is nearly identical to that of sulfur burning plants. When sulfide ores are the source of sulfur, the cost may be as much as three times that of the sulfur burning plant.

Effluent from Contact Plants

Exit gas from the absorber accounts for the major portion of emissions from contact sulfuric acid plants. This gas contains unreacted sulfur dioxide, sulfuric acid spray and mist, and unabsorbed sulfur trioxide. Tail gases containing SO_3 hydrate form a finely divided mist upon contact with atmospheric moisture. The particle size of these mists can range from submicron to 10 microns and larger. Smaller particles have greater light-scattering effect, so as particle size decreases, the plume becomes more dense. Contact plant emissions range from 7 to 95 wt. % less than 3 μ . A report by G. R. Gillespie[44] gives particle size distribution data of sulfuric acid from the waste gases of a contact acid plant, and also of sulfuric acid made from SO_3 and water under laboratory conditions, as measured with a jet impactor. The field work was conducted at the Krummrich Contact Plant in Monsanto, Illinois, and the gases were sampled from a point in the exit stack of two units approximately three feet from the absorption towers. Two samples were extracted from each of the two units by a sampling train consisting of a cyclone, a four-stage impactor, and a fine



SPENT ACID
SULFUR
FUEL OIL
AIR
FURNACE
DUST COLLECTOR
STEAM
WASTE HEAT BOILER
WATER
GAS SCRUBBER
WATER
GAS COOLER
ELECTROSTATIC PRECIPITATORS
DRYING TOWER
SO_2 STRIPPER
AIR
BLOWER
MIST ELIMINATOR
HEAT EXCHANGERS
CONVERTER
TO ATMOS-PHERE
ABSORPTION TOWER
OLEUM
ACID TRANSFER
WATER
PRODUCT
98% ACID PUMP TANK
ACID COOLERS
PRODUCT
COOLER
93% ACID PUMP TANK

Figure 55. Basic flow diagram of contact-process sulfuric acid plant burning spent acid.[43]

glass wool filter. The size fractionations of the impactor were 1.36, 0.77, 0.39, and 0.21 microns (diameter) and the size distributions obtained are shown in Figure 56. The flow rates (at 1 atmos. and 150°F) in the two stacks were 6800 cfm and 15,700 cfm with respective mist loadings of 0.73 mg/l and 0.62 mg/l.

Precipitator Design for Sulfuric Acid Plants

Electrostatic precipitators are highly effective when used for collection of acid mist. Typically, the design for an acid mist precipitator is of the wire-in-tube type shown in Figure 57 though the wire-and-plate design is common in Europe. The wire-in-tube electrostatic precipitator shown in the figure contains lead alloy tubes mounted between lead-covered tube plates. The discharge electrodes consist of lead-covered steel cable in which the cross-section of the sheath forms a six-pointed star to give sharp edges to enhance corona discharge. The ionizing electrodes are suspended from metal bars attached to lead-covered cross-pieces supported by the heavy high-tension leads. Because of possible shorting-out of the high voltage system, the sealing of the high tension leads is of paramount importance. This can be accomplished by oil seals, but, because of the risk of fire, these have been superseded in many cases by a closed chamber at the top of the precipitator which houses the insulators carrying the lead-in wire and electrode connection. Condensation of moisture on the insulator surface is prevented by feeding dried and purified air into the chamber. Steam coils with a water-repellant silicone film can be fitted around the insulators to accomplish the same purpose.

Gas flows for acid mist precipitators range from about 10,000 to 30,000 cfm at gas temperatures of 100°F to 180°F. To meet these requirements, together with a high collection efficiency, the following basic design parameters are typically used:

Basic Parameter	Range
Precipitation rate	0.20-0.30 ft/sec
Specific collection surface	200-400 sq ft/1000 cfm
Pipe diameter	10 in.
Gas velocity	3-6 ft/sec
Corona power	100-500 watts/1000 cfm
Corona power density	0.5-2.0 watts/sq ft
Rectifier voltage	75-100 kV peak

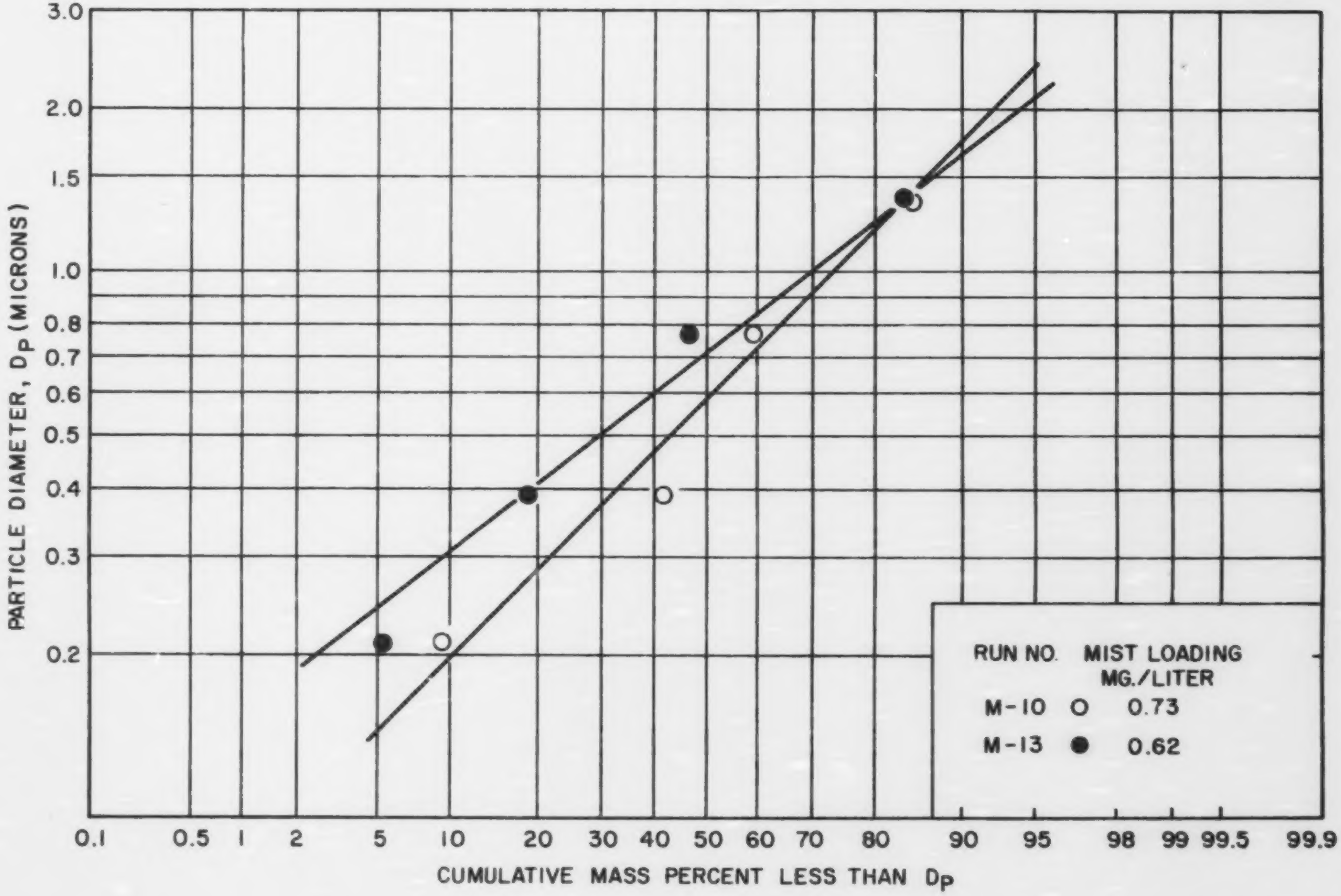


Figure 56. Particle size distribution of sulfuric acid mist from commercial contact plants.[44]

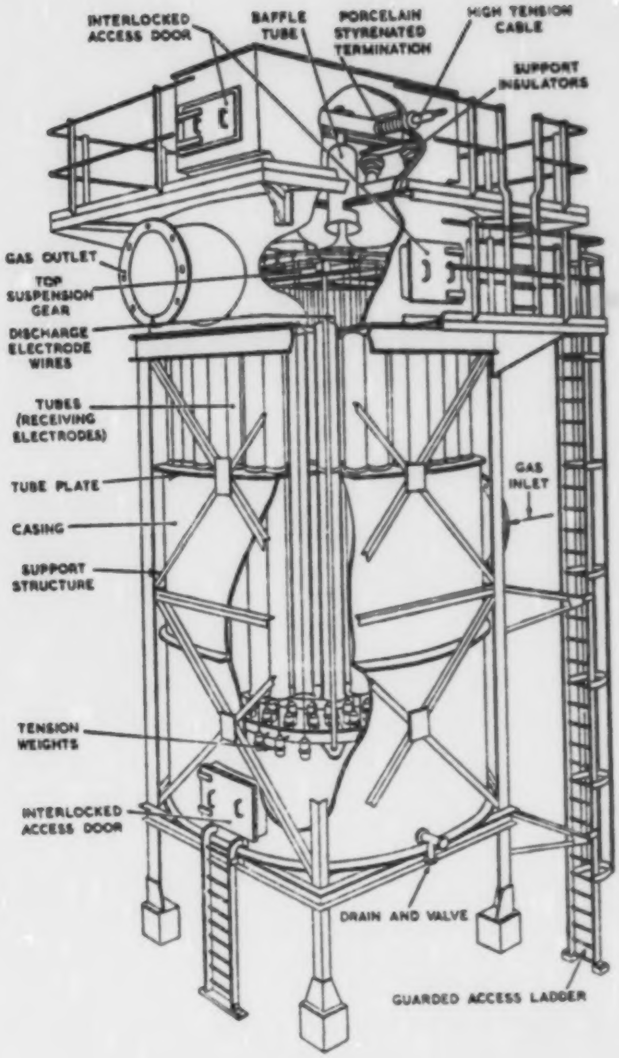

INTERLOCKED ACCESS DOOR
BAFFLE TUBE
PORCELAIN STYRENATED TERMINATION
HIGH TENSION CABLE
SUPPORT INSULATORS
GAS OUTLET
TOP SUSPENSION GEAR
DISCHARGE ELECTRODE WIRES
TUBES (RECEIVING ELECTRODES)
TUBE PLATE
CASING
SUPPORT STRUCTURE
GAS INLET
TENSION WEIGHTS
INTERLOCKED ACCESS DOOR
DRAIN AND VALVE
GUARDED ACCESS LADDER

Figure 57. Wire-in-tube acid mist precipitator.[39]

Very little design data concerning plate-type mist precipitators has been uncovered in the literature search. However, the Air Pollution Engineering Manual describes briefly a lead-lined, two-stage precipitator designed to handle 20,000 cfm tail gas from a 300 ton/day contact sulfuric acid plant.[45] Conditioned gas flows to the precipitator ionizing section, which consists of about 75 grounded curtain electrodes and 100 electrode wire extensions. The gas then flows to the precipitation section where there are twelve 14' x 14' lead plates and 375 electrode wires supplied 75,000 volts DC by a battery of silicon rectifiers. All structural material in contact with the acid mist is lead clad, and electrical wires are stainless steel cores with lead cladding.

Performance Statistics and Cost Data for Sulfuric Acid Mist Precipitator Installations

Research Cottrell has summarized critical process and electrostatic precipitator operating parameters, and these data are given in the following graphs and tables.[46] Tables 27 through 31 summarize for the years 1945-1969 the precipitator gas velocity, inlet mist loading, inlet gas temperature, and input power and field strength. The number of installations and precipitators, and total gas volumes involved in the statistical analyses are also presented.

Precipitator cost data on an installed basis are presented in terms of cost versus gas flow rate for several efficiency levels for the period 1960 to 1969. Limited data on FOB precipitator cost are included. The data are summarized in Table 32 and Figure 58. The spread in data is indicated by the arrows on the figure. The scatter in cost data, at a given efficiency and gas rate, can be attributed to many factors, the most important ones being the size of the precipitator as related to mist characteristics, primarily particle size, and gas conditions; the geographical location of the installation (particularly for erected cost since labor cost can vary considerably across the country); the pricing-profit policy of various corporations bidding on the job; whether the installation is a backfit or upgrading of an existing installation which may require additional improving to "shoehorn" the precipitator into the overall installation; and the type and degree of sophistication of the electrical system.

The performance of sulfuric acid precipitators has been reported in terms of the ratio of the actual value to the design value of precipitation rate parameter (w). The ratio (R) is defined as the ratio of performance w to the design w and is therefore the ratio of actual performance to the anticipated performance. For instance, a value of R = 1.20 indicates that the precipitator size is 20% larger than required to meet the guarantee efficiency for that particular unit. Table 33 summarizes the data used in

TABLE 27[39]

PRECIPITATOR INLET MIST LOADING

Summary of Performance Statistics
Sulfuric Acid Mist Precipitator
(1945 - 1969)

Pptr. Inlet Load gr/SCFD	No. of Install.	No. of Pptr.	Pptr. Capacity Thousand ACFM In Interval	% of Install. In Loading Interval
0-0.19	1	1	16.5	4.3
0.2-0.39	3	4	31.9	13.0
0.4-0.59	4	8	122.3	17.4
0.6-0.79	3	5	88.5	13.0
0.8-0.99	3	6	79.6	13.0
1.0-1.19	0	0	0	0
1.2-1.39	0	0	0	0
1.4-1.59	3	4	57.9	13.0
1.6-1.79	1	2	36	4.3
1.8-1.99	1	2	28.1	4.3
2.0-2.19	1	2	33	4.3
2.2-2.39	0	0	0	0
2.4-2.59	2	2	27	8.7
4.0-4.19	1	1	10.2	4.3
Totals	23	37	531	100

TABLE 28[39]

Precipitator Inlet Gas Temperature

Summary of Performance Statistics
Sulfuric Acid Mist Precipitator
(1945-1969)

Inlet Gas Temp. °F	No. of Install.	No. of Pptr.	Pptr. Capacity Thousand ACFM In Interval	% of Install. In Temperature Interval
60-79.9	0	0	0	0
80-99.9	6	11	139	26.1
100-109.9	5	5	37.9	21.7
120-139-9	1	2	12.0	4.3
140-159.9	4	9	95.1	17.4
160-179.9	7	8	221.8	30.4
180-199.9	0	0	0	0
Totals	23	35	505.8	100

TABLE 29[39]

Precipitator Input Power

Summary of Performance Statistics
Sulfuric Acid Mist Precipitator
(1945 - 1969)

Input Power, Watts/1000 ACFM	No. of Install.	No. of Pptrs.	Pptr. Capacity Thousand ACFM In Interval	% of Install. In Power Interval
0-99.9	0	0	0	0
100-199.9	2	2	20.7	15.4
200-299.9	2	4	41.0	5.4
300-399.9	3	5	101.0	23.1
400-499.9	2	3	40.1	15.4
500-599.9	1	1	10.2	7.7
600-699.9	2	2	47.8	15.4
700-799.9	0	0	0	0
800-899.9	0	0	0	0
900-999.9	1	1	8.0	7.7
Totals	13	18	268.8	100

TABLE 30[39]

PRECIPITATOR FIELD STRENGTH

Summary of Performance Statistics
Sulfuric Acid Mist Precipitator
(1945-1969)

Field Strength KV/inch	No. of Install.	No. of Pptrs.	Pptr. Capacity Thousand ACFM In Interval	% of Install. In Interval
8-8.4	0	0	0	0
8.5-8.9	1	2	17.0	7.1
9-9.4	1	3	42	7.1
9.5-10.9	0	0	-	0
10-10.4	3	6	127.8	21.4
10.5-10.9	0	0	-	0
11-11.4	2	3	25.8	14.3
11.5-11.9	2	4	61	14.3
12-12.9	3	4	59.1	21.4
12.5-12.9	2	3	43.5	14.3
Totals	14	25	376.2	100

TABLE 31[39]

Precipitator Gas Velocity

Summary of Performance Statistics
Sulfuric Acid Mist Precipitator
(1945-1969)

Velocity Interval FPS	No. of Install.	No. of Pptrs.	Pptr. Capacity Thousand ACFM In Velocity Interval	% of Install. in Velocity Interval
1.5-1.9	0	0	0	0
2-2.4	1	1	28.75	4.8
2.5-2.9	1	11	8	4.8
3-3.4	6	2	143.3	28.6
3.5-3.9	2	4	23.2	9.5
4-4.4	2	8	58.2	9.5
4.5-4.9	5	8	127.9	23.8
5-5.4	0	0	0	0
5.5-5.9	1	2	33	4.8
6-6.4	1	2	25	4.8
6.5-6.9	1	2	25	4.8
7-7.4	0	0	0	0
7.5-7.9	1	1	16.5	4.8
Totals	21	42	488.9	100

TABLE 32[39]

Summary of Sulfuric Acid Mist
Precipitator Costs 1960-1969

Efficiency Range	0 - 10,000 cfm				10,000 - 25,000 cfm				25,000 - 50,000 cfm			
	1965-1969		1960-1965		1965-1969		1960-1965		1965-1969		1960-1965	
	FOB*	Erected*	FOB	Erected	FOB	Erected	FOB	Erected	FOB	Erected	FOB	Erected
90 - 95	-	-	-	-	-	-	-	-	-	2.21 (1)	-	-
95 - 99	-	-	14.5 (1)	6.00 (1)	3.77 (1)	5.84 (4)	-	-	-	4.65 (1)	-	3.94 (2)
99+	-	-	-	-	-	-	-	-	-	-	-	-

Efficiency Range	50,000 - 100,000 cfm				> 100,000 cfm			
	1965-1969		1960-1965		1965-1969		1960-1965	
	FOB	Erected	FOB	Erected	FOB	Erected	FOB	Erected
90 - 95	-	-	-	-	-	-	-	-
95 - 99	-	6.22 (1)	2.93 (1)	-	-	2.53 (5)	-	-
99+	-	3.71 (3)	-	-	-	-	-	-

*Note: Costs are $/acfm. Number in parentheses is number of installations on which contract prices were averaged.

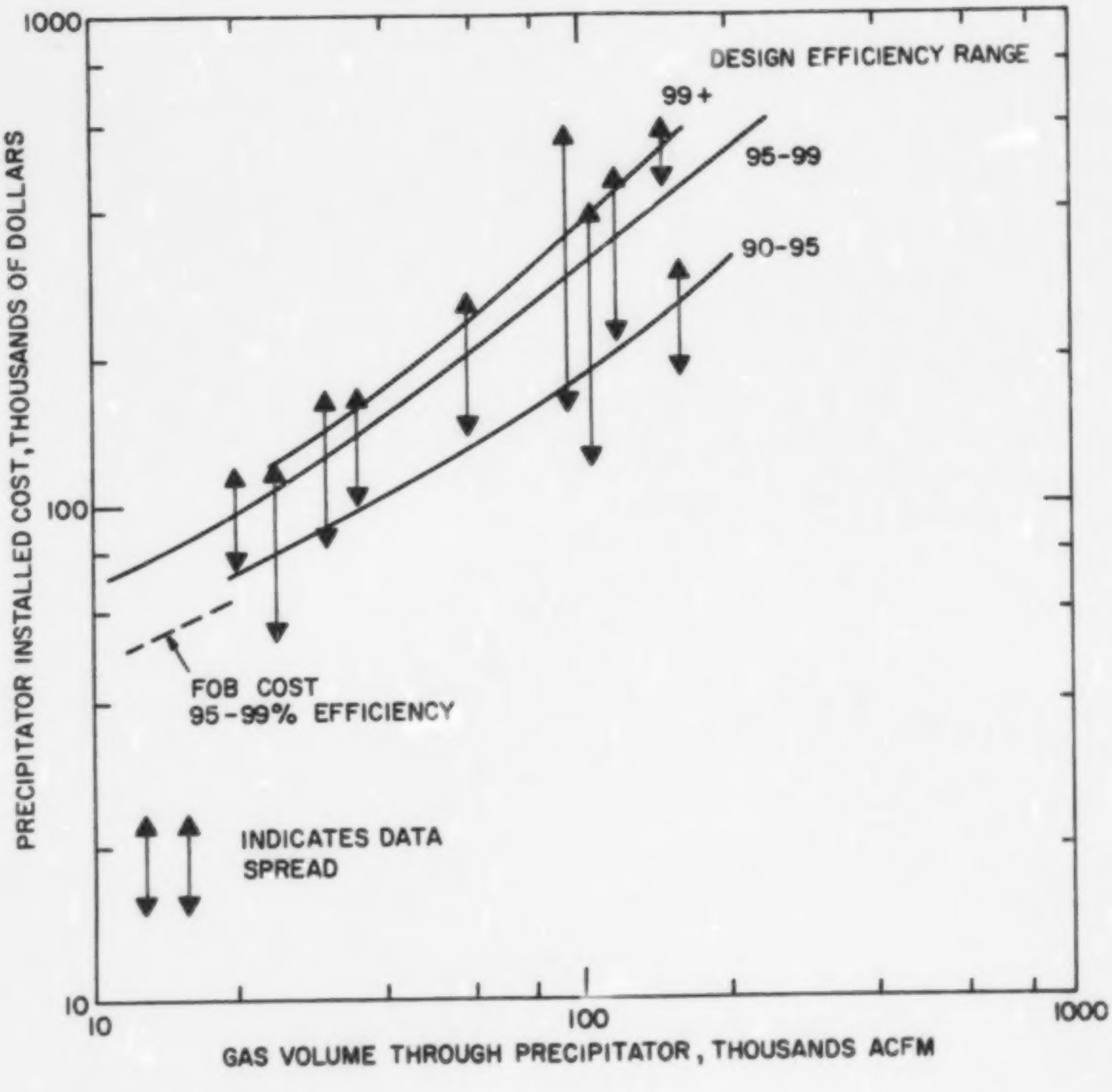


Figure 58. Installed Cost of Sulfuric Acid Mist Precipitators, 1965-1969.[39]

TABLE 33[39]

DISTRIBUTION OF RATIO (R) FOR SULFURIC ACID MIST PRECIPITATORS (1945 - 1969)

$R = W_P/W_D$ Interval	No. of Install.	No. of Pptrs.	Pptr. Capacity Thousand ACFM In Interval	% of Installations In Interval
0.5-0.59	1	2	36	4.5
0.6-0.69	2	3	53.8	9.1
0.7-0.79	2	3	41	9.1
0.8-0.89	1	2	57.5	4.5
0.9-0.99	2	4	50.2	9.1
1.0-1.09	4	6	76.1	18.2
1.1-1.19	2	2	20.4	9.1
1.2-1.29	3	5	57.2	13.6
1.3-1.39	4	7	96.8	18.2
1.4-1.49	1	2	36.0	4.5
1.5-1.59	0	0	0	0
TOTALS	22	36	525.0	100

the statistical analysis in which a total of 22 installations consisting of 36 acid mist precipitators were examined. The ratio for all the installations was distributed between 0.5 and 1.50.

Phosphoric Acid Production

Phosphoric acid is manufactured by two processes: (1) the thermal process, involving the burning of elemental phosphorus to the pentoxide, followed by hydration, and (2) the wet process, involving the treatment of phosphate rock with sulfuric acid. Since the literature search thus far has revealed extensive use of mist electrostatic precipitators for acid mist collection for the thermal process only, the following discussion will not include information on the wet process.

In its simplest form, manufacture of phosphoric acid by the thermal process involves three steps:

1. Oxidizing liquid elemental phosphorus in a cylindrical combustion chamber to produce phosphorus pentoxide,

   $$P_4 + 5O_2 \rightarrow P_4O_{10}$$

2. Hydrating the phosphorus pentoxide with dilute acid or water to produce phosphoric acid liquid and mist,

   $$P_4O_{10} + 6H_2O \rightarrow 4H_3PO_4$$

3. Removal of the phosphoric acid mist from the gas stream, usually accomplished by scrubber, mist eliminators, or electrostatic precipitators.

A typical flow diagram for thermal process manufacture of phosphoric acid is given in Figure 59.[47] The phosphorus is transferred from the liquid phosphorus feed tank to the burner tower when the phosphorus is mixed with air and oxidized. The resulting phosphorus pentoxide vapor and excess air then pass into a hydration tower from which the product acid discharges. The weak acid collected in the abatement equipment is recycled within the process.

The principal emission from the manufacture of phosphoric acid by the thermal process is acid mist in the absorber discharge gas. The particle size of the acid mist ranges from 0.2 to 2.6 microns with a mass median diameter of 1.6 microns.[48]

Collection of Phosphoric Acid Mists

Packed and open tower scrubbers, venturi scrubbers, cyclonic separators with wire mesh eliminators, fiber mist eliminators,

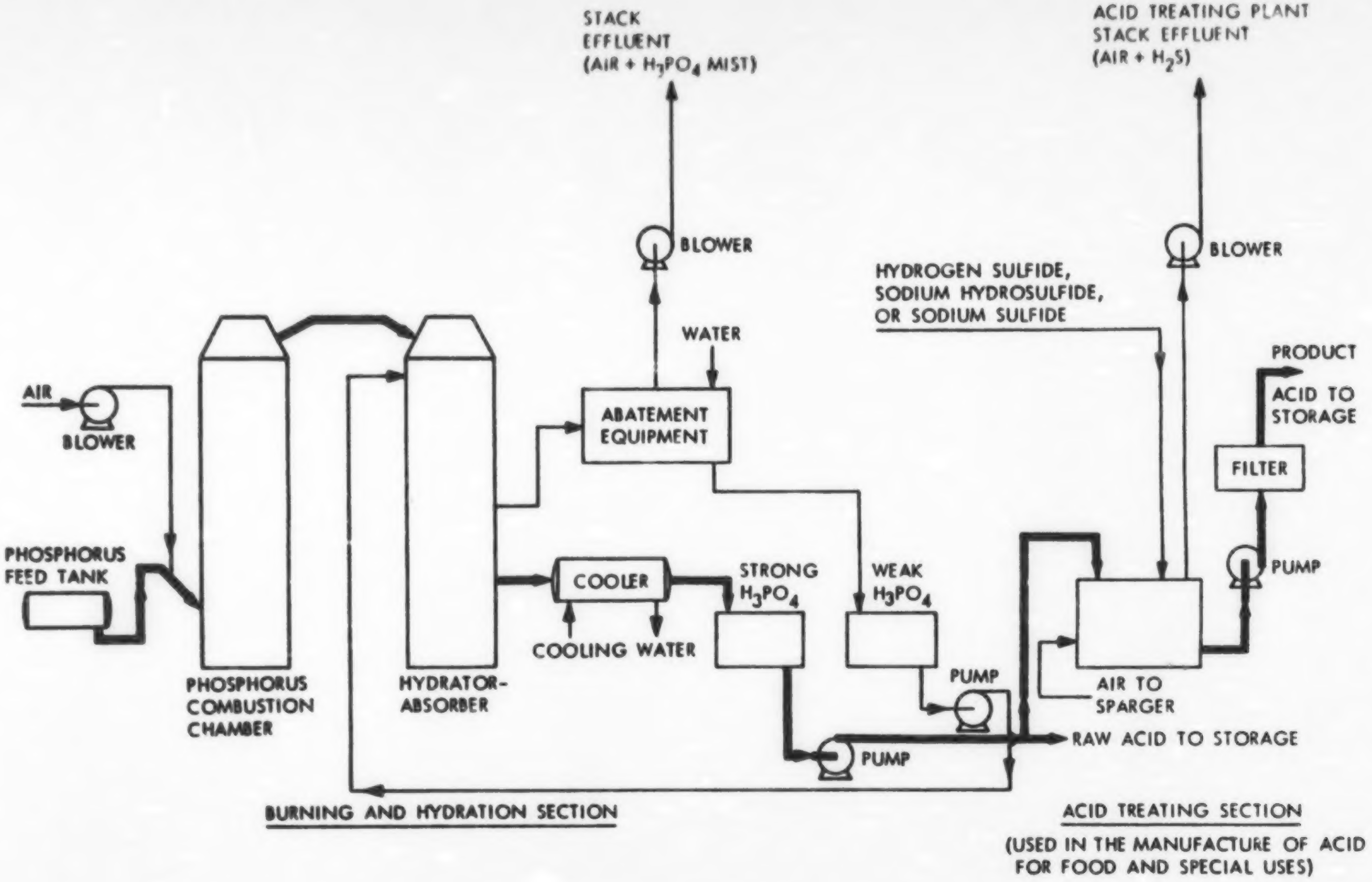

STACK
EFFLUENT
(AIR + H_3PO_4 MIST)
ACID TREATING PLANT
STACK EFFLUENT
(AIR + H_2S)
BLOWER
BLOWER
HYDROGEN SULFIDE,
SODIUM HYDROSULFIDE,
OR SODIUM SULFIDE
WATER
PRODUCT
ACID TO
STORAGE
AIR
BLOWER
ABATEMENT
EQUIPMENT
FILTER
PHOSPHORUS
FEED TANK
COOLER
STRONG
H_3PO_4
WEAK
H_3PO_4
PUMP
COOLING WATER
PHOSPHORUS
COMBUSTION
CHAMBER
HYDRATOR-
ABSORBER
PUMP
AIR TO
SPARGER
RAW ACID TO STORAGE
PUMP
BURNING AND HYDRATION SECTION
ACID TREATING SECTION
(USED IN THE MANUFACTURE OF ACID
FOR FOOD AND SPECIAL USES)

Figure 59. Flow Diagram for Typical Thermal-Process Phosphoric Acid Plant[47]

high energy wire mesh contactors, and mist electrostatic precipitators have all been used to collect phosphoric acid mist from thermal-process phosphoric acid manufacture.

The typical design for a mist precipitator for phosphoric acid collection consists of a single-stage, vertical flow, pipe-type unit. Stainless steel is the conventional material of construction instead of lead because of temperatures which may fluctuate above the softening point of lead. The collecting electrodes, normally stainless, are of variable diameter and require no cleaning because of the free-flowing nature of the precipitate. Inlet temperatures are usually below 200°F with grain loadings, which vary considerably, typically being 10-60 gr/scf (H_3PO_4 basis). Typical voltage requirements are about 75 kV supplied by various electrical energization systems. TVA has used precipitators for many years to reduce phosphoric acid emissions, and the construction details of a large precipitator operated by the TVA are shown in Figure 60.[49] All stainless steel used on this unit is American Iron and Steel Institute type 316. Electric current is supplied from a half-wave rectifier by electrical leads entering the precipitator through lead-lined oil seals which contain insulators. A stainless steel fan pulls 9.4 m^3/sec of gases at 106°C through the three parallel sections of the precipitator, which collects 99% of the fine mist. The precipitator is followed by a water scrubber.

Since high concentrations of phosphoric acid mist are often present in process streams and since the particle size of the mist is small, large precipitators are usually required. Two mist electrostatic precipitators are often used in series to meet the high efficiency requirements rather than the single section as depicted in the figure. In general, phosphoric acid losses from a mist precipitator are affected only slightly by the rate of gas flow or by temperature so long as the gas flow is below design rate. However, cleanliness of the equipment and electrical conditions employed affect such losses materially.

ALUMINUM INDUSTRY

Primary aluminum production, as used in this report, will include the smelting and refining of aluminum as opposed to secondary aluminum production which is primarily engaged in the recovery of aluminum from scrap. There are 27 primary aluminum smelters in the United States with plant capacities ranging from 80,000 to 275,000 tons per year, the locations, capacities, and cell types of which are shown in Table 34.[50] Aluminum, produced from alumina (Al_2O_3) by electrolytic reduction in fused

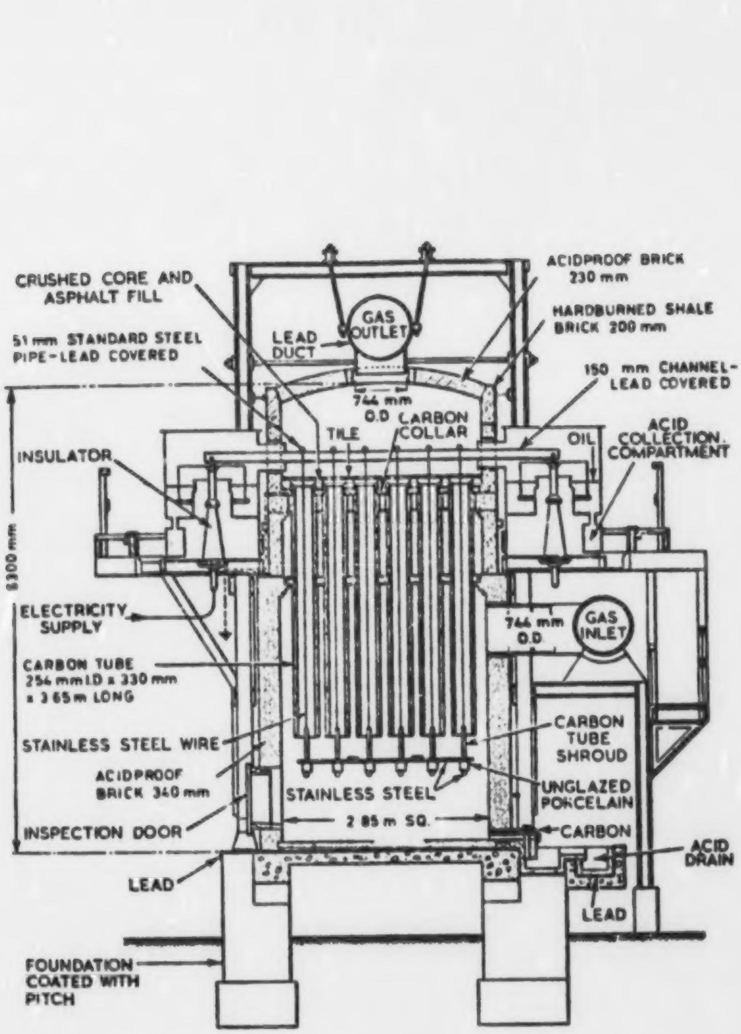

CRUSHED CORE AND ASPHALT FILL
ACIDPROOF BRICK 230 mm
GAS OUTLET
LEAD DUCT
HARDBURNED SHALE BRICK 200 mm
51 mm STANDARD STEEL PIPE-LEAD COVERED
150 mm CHANNEL-LEAD COVERED
744 mm O.D
TILE
CARBON COLLAR
OIL
ACID COLLECTION. COMPARTMENT
INSULATOR
8300 mm
ELECTRICITY SUPPLY
744 mm O.D
GAS INLET
CARBON TUBE 254 mm I.D x 330 mm x 3.65 m LONG
STAINLESS STEEL WIRE
CARBON TUBE SHROUD
ACIDPROOF BRICK 340 mm
STAINLESS STEEL
UNGLAZED PORCELAIN
2.85 m SQ.
INSPECTION DOOR
CARBON
ACID DRAIN
LEAD
LEAD
FOUNDATION COATED WITH PITCH

Figure 60. Electrostatic precipitator used for P_2O_5 mist removal.[49]

TABLE 34[50]

PLANT CAPACITY FOR MANUFACTURING PRIMARY ALUMINUM

State and City	Annual Capacity, Tons	Company	Reduction Cell Types*
Alabama			
Sheffield	221,000	Reynolds	HS
Scottsboro	210,000	Revere	PB
Arkansas			
Arkadelphia	63,000	Reynolds	HS
Jones Mills	122,000	Reynolds	PB
Indiana			
Evansville	175,000	Alcoa	PB
Kentucky			
Hawesville	45,000	National-Southwire Aluminum	PB
Louisiana			
Chalmette	260,000	Kaiser	HS
Lake Charles	35,000	Gulf Coast Aluminum	PB
Maryland			
Frederick	90,000	Eastalco	PB
Missouri			
New Madrid	110,000	Noranda	PB
Montana			
Columbia Falls	175,000	Anaconda	VS
New York			
Messena	128,000	Reynolds	HS
	125,000	Alcoa	PB
North Carolina			
Badin	100,000	Alcoa	PB
Ohio			
Hannibal	240,000	Ormet	PB
Oregon			
The Dalles	87,000	Martin Marietta	VS
Trontdale	100,000	Reynolds	PB
Tennessee			
Alcoa	200,000	Alcoa	all
New Johnsonville	140,000	Conalco	PB
Texas			
Corpus Christi	110,000	Reynolds	HS
Point Comfort	175,000	Alcoa	VS
Rockdale	275,000	Alcoa	PB
Washington			
Bellingham	265,000	--------	PB
Longview	190,000	Reynolds	HS
Tacoma	81,000	Kaiser	HS
Spokane	206,000	--------	PB
Vancouver	100,000	Alcoa	PB
Wenatchee	175,000	Alcoa	PB
West Virginia			
Ravenswood	163,000	Kaiser	PB

* PB = Prebaked Anode
HS = Horizontal Stud Soderberg
VS = Vertical Stud Soderberg

cryolite ($AlF_3 \cdot 3NaF$), passes through three stages from ore to metal: bauxite, alumina, and primary aluminum. In most cases the Bayer process, shown in Figure 61, is used to refine alumina from bauxite.[51] The alumina is next sent to a primary aluminum processing plant where it is converted to the metal by electrolysis.

Process Description

The Hall-Heroult process is used by all domestic primary aluminum producers for the electrolytic reduction of purified alumina to aluminum metal. The process involves the dissolving of alumina in a bath of molten cryolite. The bath is less dense than molten aluminum and is maintained in a molten state in a carbon crucible known as a "cell" or "pot". The carbon crucible serves as the cathode, and a carbon block serves as the anode. Electrolysis decomposes the alumina into aluminum and oxygen, and because of its greater density, the aluminum sinks to the bottom of the cell. Periodically the aluminum metal is withdrawn, and fresh alumina feed and bath chemicals are added by piercing the frozen crust of the bath. This "crust breaking" agitates the bath and is a time of increased particulate and gaseous emissions.

Classes of Electrolytic Cells Employed in Hall-Heroult Process

The variations of cell construction are based on the method of anode manufacture, and the effluent characteristics from each cell differ in type and quantity. Reduction cells are of three basic types: prebaked cells which use prebaked carbon anodes, and two types of Soderberg cells which use large single anodes continuously baked in place over the bath. In all cell types the anode is composed of coke bound with pitch.

Prebaked or Niagara Cell (Illustrated in Figure 62)[52] -

Prebaked potlines employ multiple blocks of preformed carbon, supported by copper and aluminum hangers to the electrical busbars overhead. The bus is adjustable to compensate for anode consumption.

Vertical Stud Soderberg (Illustrated in Figure 63)[53] -

The vertical stud Soderberg cell, because of the placement of the anode studs in a vertical position, allows gases liberated by the cell to be hooded most easily of the cell types. Carbon paste is added to the top of the cell and slowly carbonized as it moves toward the bath. The vertically positioned metal studs carry electric current to the carbonized portion through the top.

Horizontal Stud Soderberg (Illustrated in Figure 64)[54] -

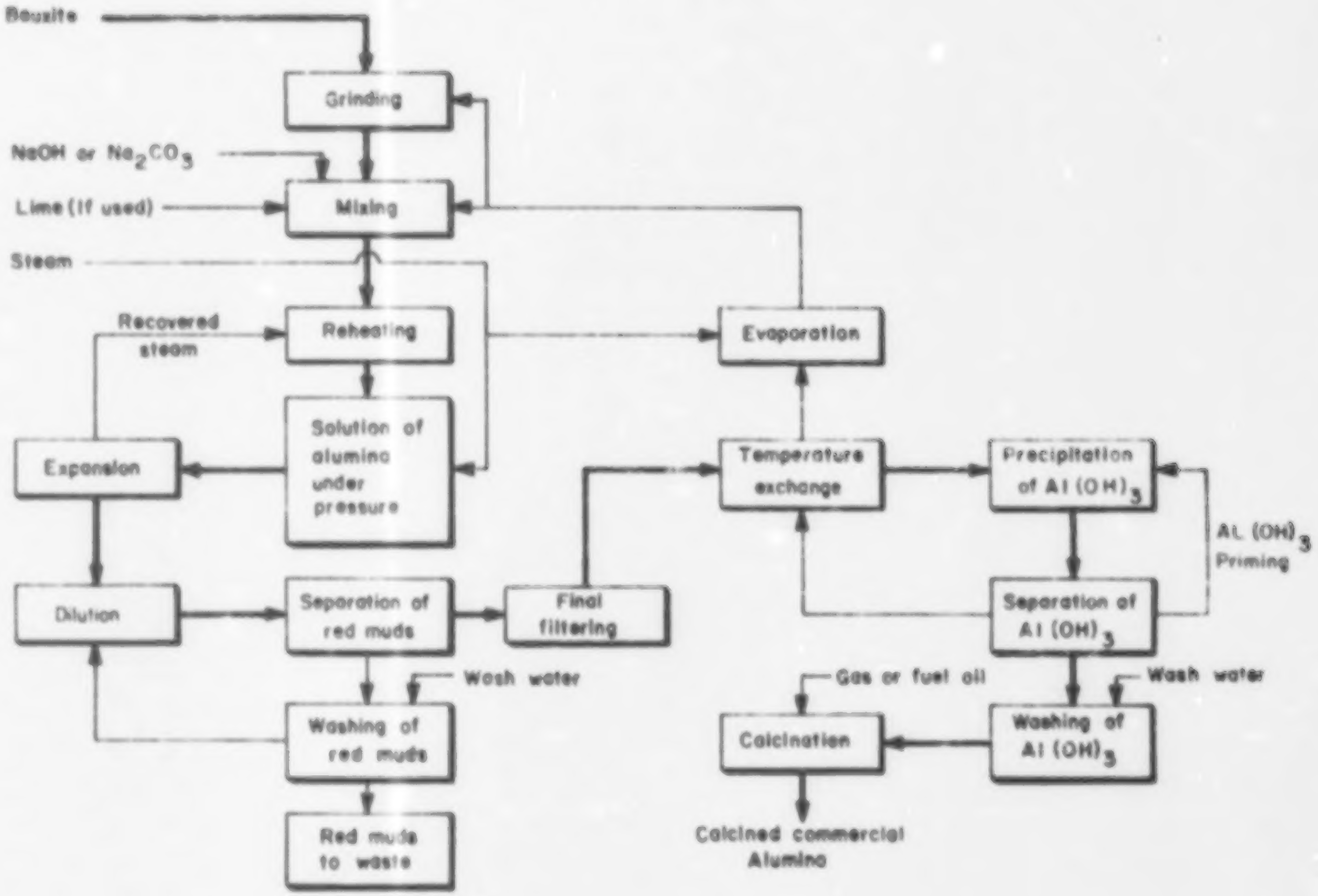

Bauxite
Grinding
NaOH or Na_2CO_3
Lime (If used)
Mixing
Steam
Recovered steam
Reheating
Solution of alumina under pressure
Expansion
Dilution
Separation of red muds
Final filtering
Wash water
Washing of red muds
Red muds to waste
Evaporation
Temperature exchange
Precipitation of $Al(OH)_3$
$Al(OH)_3$ Priming
Separation of $Al(OH)_3$
Gas or fuel oil
Wash water
Calcination
Washing of $Al(OH)_3$
Calcined commercial Alumina

Figure 61. Diagram of the Bayer Process[51]

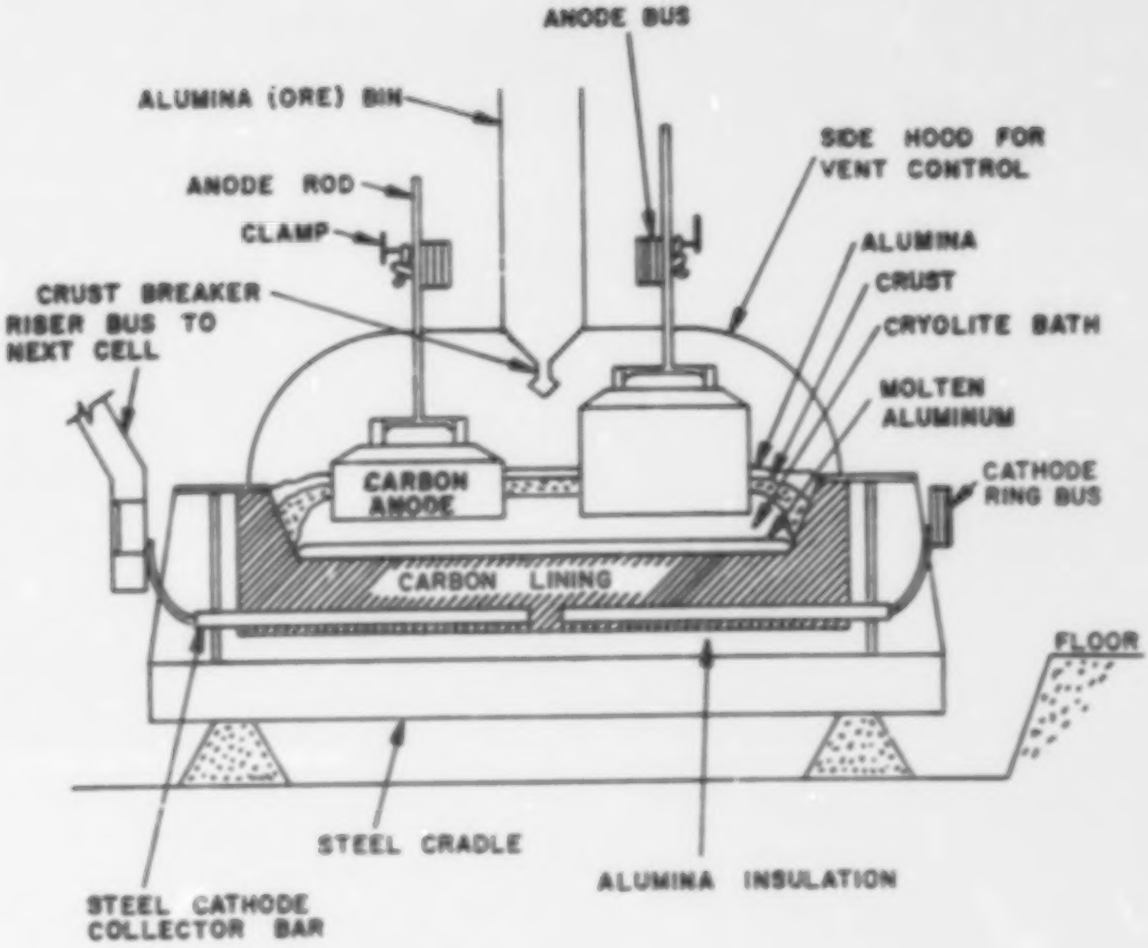

ANODE BUS
ALUMINA (ORE) BIN
SIDE HOOD FOR VENT CONTROL
ANODE ROD
CLAMP
ALUMINA
CRUST
CRUST BREAKER
RISER BUS TO NEXT CELL
CRYOLITE BATH
MOLTEN ALUMINUM
CARBON ANODE
CATHODE RING BUS
CARBON LINING
FLOOR
STEEL CRADLE
ALUMINA INSULATION
STEEL CATHODE COLLECTOR BAR

Figure 62. Prebake Reduction Cell Schematic Arrangement[62]

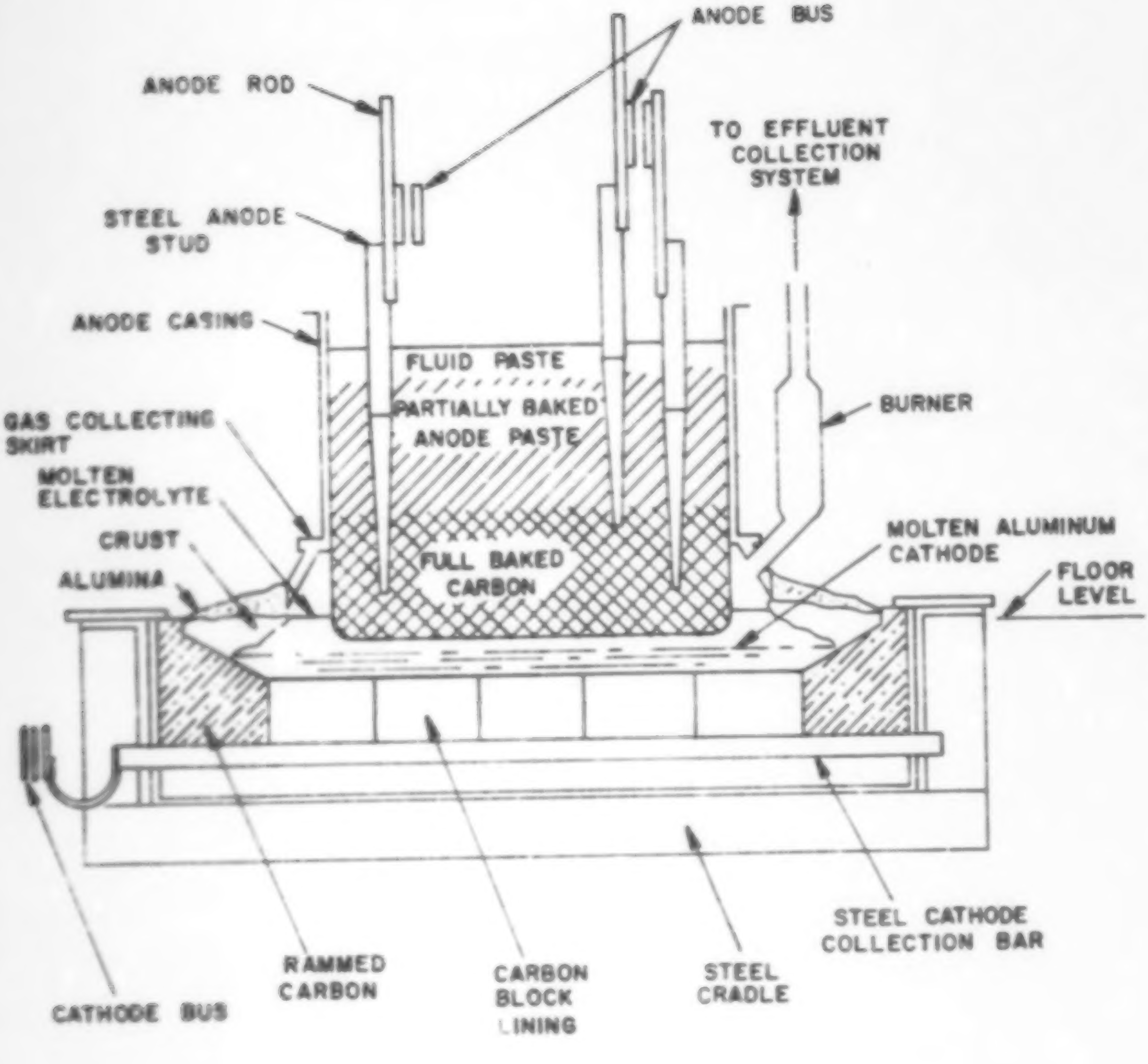

ANODE BUS
ANODE ROD
TO EFFLUENT COLLECTION SYSTEM
STEEL ANODE STUD
ANODE CASING
FLUID PASTE
PARTIALLY BAKED ANODE PASTE
BURNER
GAS COLLECTING SKIRT
MOLTEN ELECTROLYTE
CRUST
ALUMINA
FULL BAKED CARBON
MOLTEN ALUMINUM CATHODE
FLOOR LEVEL
STEEL CATHODE COLLECTION BAR
RAMMED CARBON
CARBON BLOCK LINING
STEEL CRADLE
CATHODE BUS

Figure 63. Vertical Stud Soderberg Cell Schematic Arrangement[53]

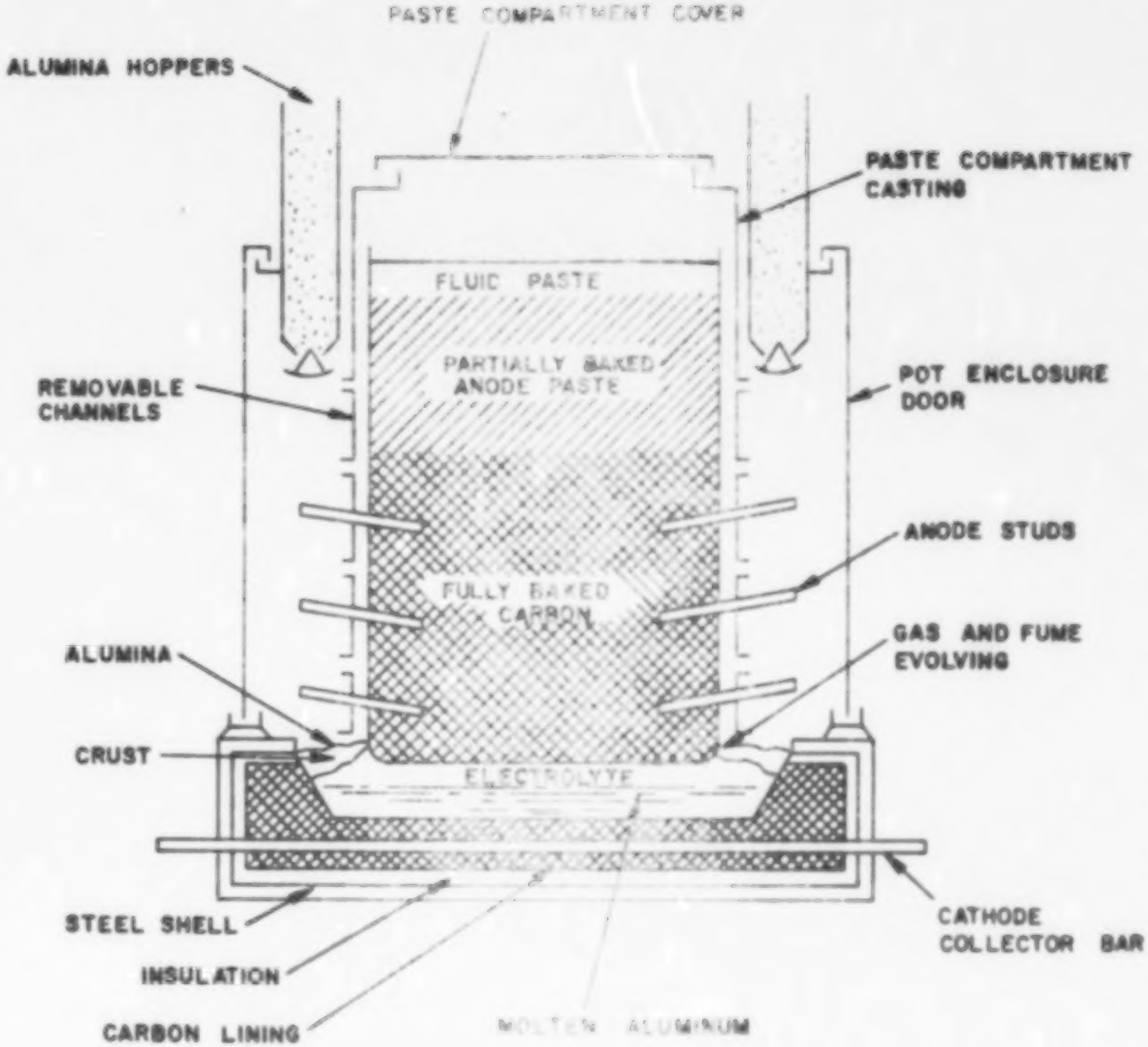

PASTE COMPARTMENT COVER
ALUMINA HOPPERS
PASTE COMPARTMENT CASTING
FLUID PASTE
PARTIALLY BAKED ANODE PASTE
REMOVABLE CHANNELS
POT ENCLOSURE DOOR
ANODE STUDS
FULLY BAKED CARBON
ALUMINA
GAS AND FUME EVOLVING
CRUST
ELECTROLYTE
STEEL SHELL
CATHODE COLLECTOR BAR
INSULATION
CARBON LINING
MOLTEN ALUMINUM

Figure 64. Horizontal Stud Soderberg Cell Schematic Arrangement[54]

Hood requirements for the horizontal stud Soderberg are much more difficult because of the location of the studs at the side of the electrode rather than at the top. Since access to the cell is necessary for electrode pin removal and replacement, burning of the gases and tars is not possible, and tar-fouling becomes a problem. Therefore, when electrostatic precipitator usage is attempted, the plates require water flushing to prevent fouling by tars.

Effluents originate at several processing operations in an aluminum smelter. Since the most difficult to control come from the potlines, this report will emphasize those effluents originating from the prebaked and Soderberg cells. The airborne effluents from the electrolytic process consist mainly of:

> CO and CO_2, formed when the released oxygen reacts with the carbon anode and escapes as CO or CO_2;
>
> SO_x, from sulfur present in the petroleum coke and pitch used to make the anodes;
>
> Particulates of vaporized bath materials;
>
> HF gas, resulting from the hydrolysis of fluoride salts;
>
> Alumina, cryolite, and aluminum fluoride dusts, entrained from the bath crust;
>
> Hydrocarbons, volatilized from the binders used to make the anode.

The quantity and type of fume emitted from reduction cells depend greatly on the cell design and operating techniques used. Reported determinations of particle size distributions of the dust and fume emissions collected from prebaked and horizontal Soderberg cells are shown in Figure 65.[55] Two plots are shown for prebake potlines, one the average of four samples of pot emissions, the other the average of five samples of electrostatic precipitator intake. Another size distribution of horizontal spike Soderberg cell emissions is presented in Figure 66.[56] This typical size distribution was determined with a cascade impactor at the exit of the cell hood on potline 4 at the Kaiser Aluminum and Chemical Corporation plant in Tacoma, Washington. Microscopic analyses were performed to verify the theoretical predictions of the University of Washington cascade impactor. The size distribution is the result

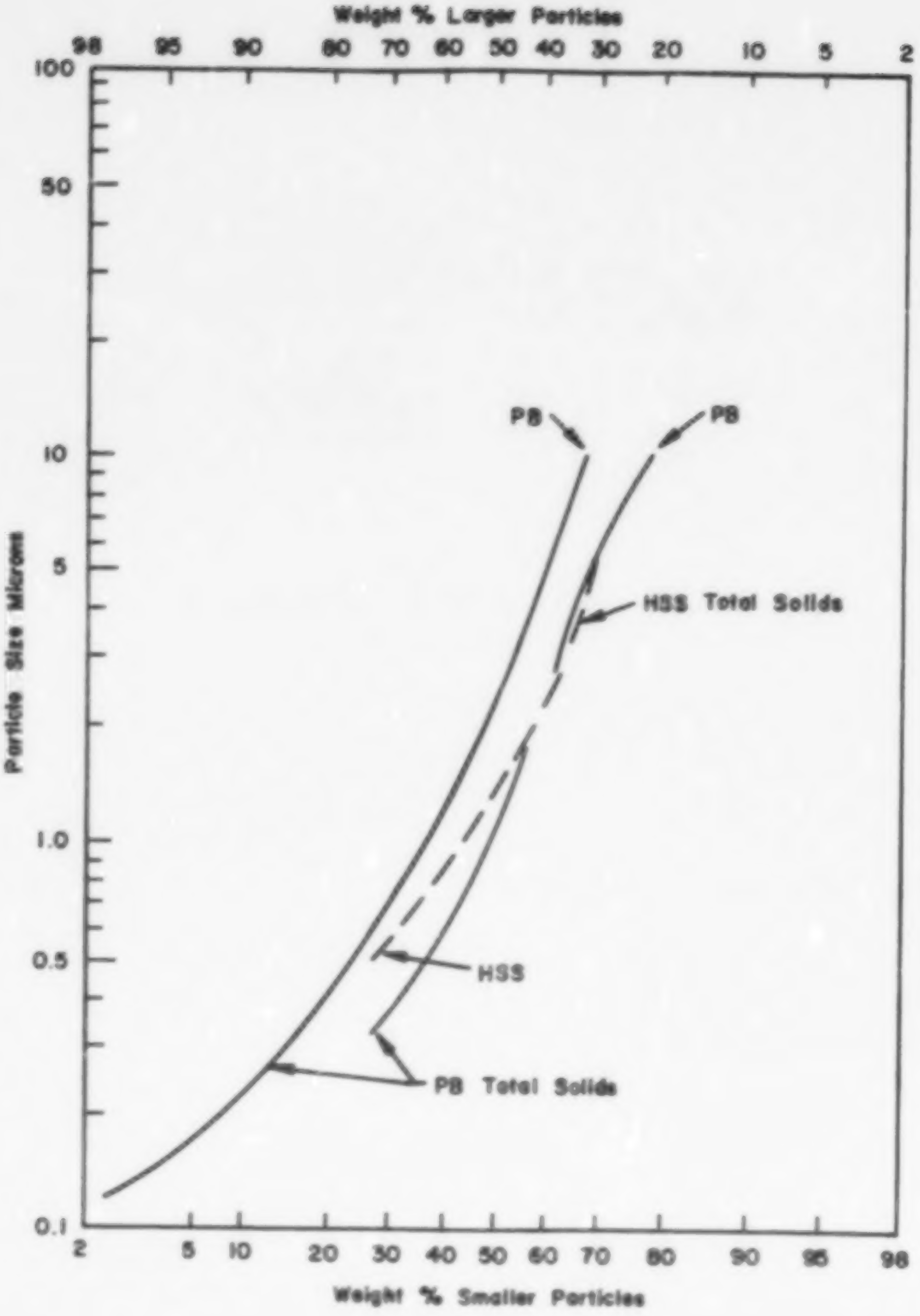


Figure 65. Particle Size Weight Distribution, Potline Primary Effluent[55]

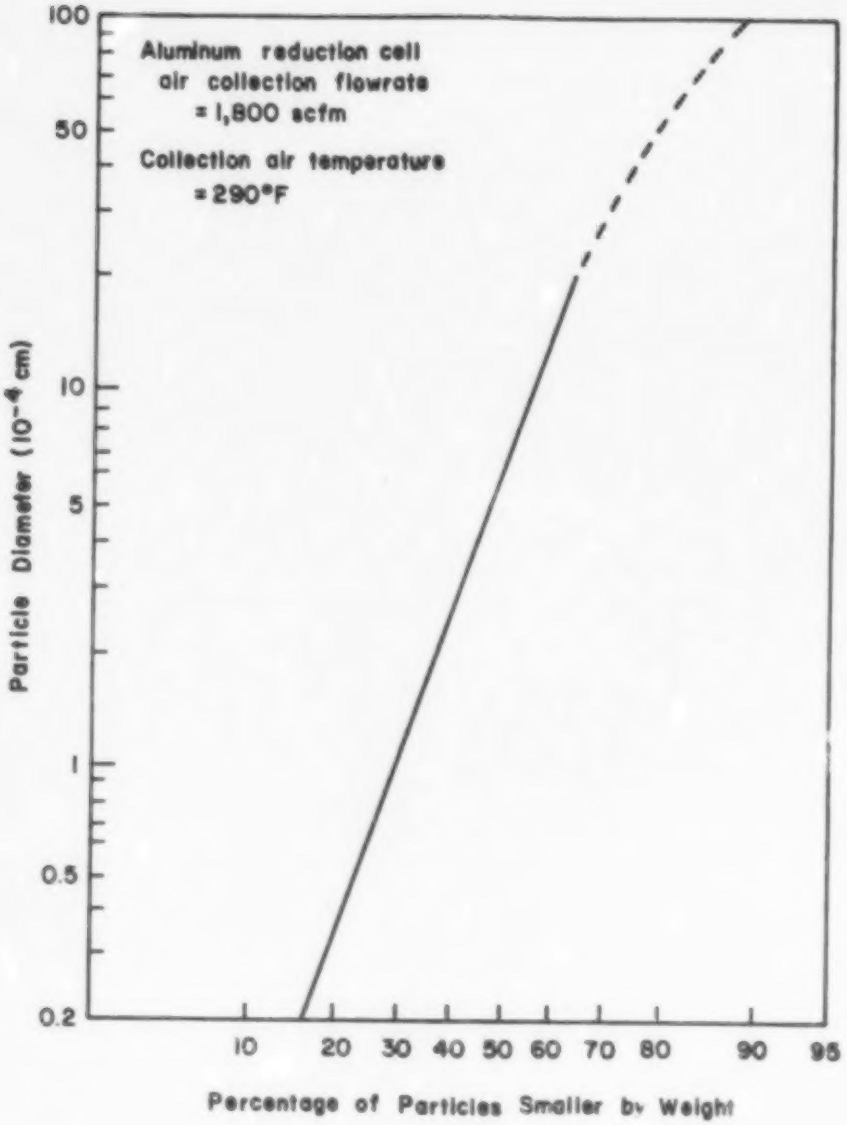


Figure 66. Composite Particle Size Distribution by Weight for Aluminum Reduction Cell Air Emissions (Kaiser Aluminum and Chemical Corporation Plant at Tacoma, Wash., Potline 4) at the Exit of the Reduction Cell.[56]

of combining all the size distribution data (140 tests) and taking into account the percentage of time each cell operation takes during a day. Particle concentration and size distribution were found to change significantly with changes in cell process operation.

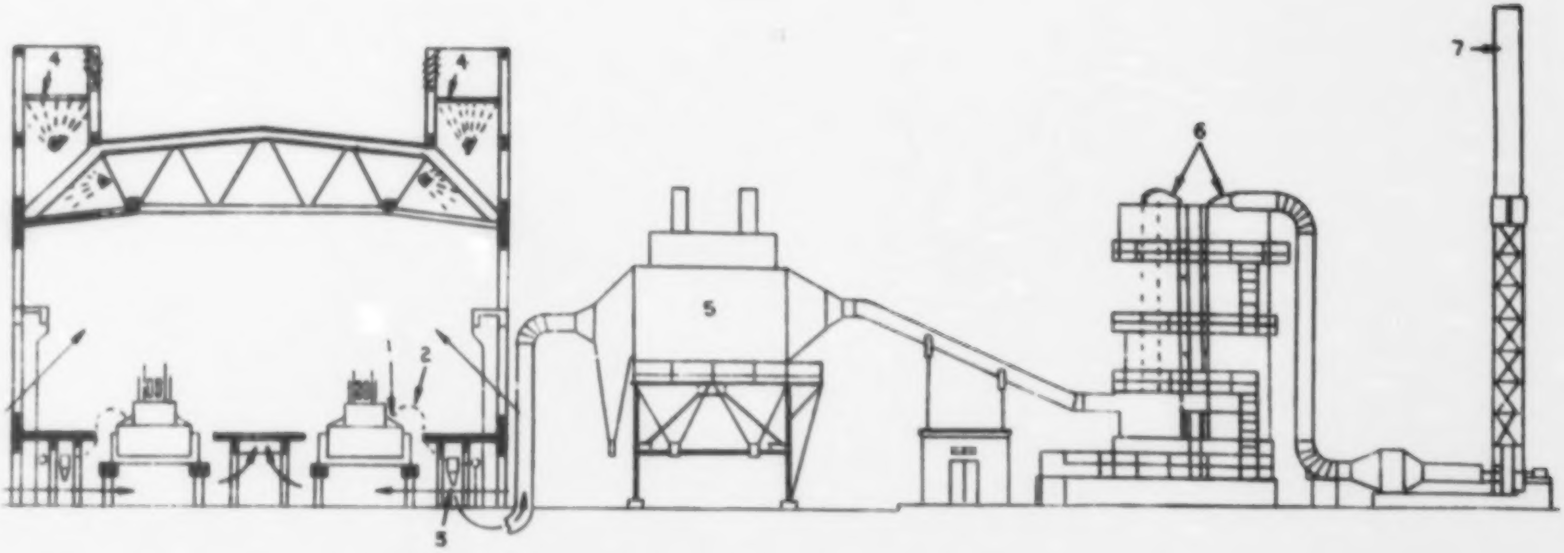
Effective control of aluminum potline effluents involves three types of collection systems which can be classed as: 1) capture of all effluents by potline hooding, 2) subsequent collection of these captured pollutants by existing control devices, and 3) scrubbing of roof "monitor" emissions. This report will deal with those collection devices utilized for collection of potline effluents which have been hooded.

While the overall pollution potential of a primary aluminum facility is not significantly affected by the anode configuration, the choice of the associated air pollution control systems is closely related to the cell type. Therefore controls will be discussed separately for the prebake and Soderberg cells.

Control devices for vertical stud Soderberg cells have included multicyclones and spray-type scrubbers. Exhausts may be treated by bag filters coated with lime or alumina, or by electrostatic precipitators, but the residual tar creates a fouling problem in the collection system. A collection system for Montecatini Edison, a plant in Milan which incorporates dry cyclones, a dry electrostatic precipitator, and two scrubbers, is shown in Figure 67.[57]

As stated earlier, hooding for the horizontal stud Soderberg cell is inherently less complete and the large volumes of air entrained during replacement and readjustment of studs creates a dilute mixture of hydrocarbons which encourages a tar-fouling problem in ducts and control equipment. Existing controls have consisted of scrubbers, but where electrostatic precipitators are attempted, the plates require water flushing to prevent fouling by tars.

Particulate emissions from prebake pots contain none of the tar found in the horizontal stud Soderberg; instead "dusting" of the carbon anode produces carbon particles in addition to alumina, etc. Current controls have consisted of dry-type cyclones or electrostatic precipitators followed by wet scrubbers.



1. Gas suction skirt
2. Burners
3. Cyclones
4. Filter screen
5. Electrofilter
6. Scrubber
7. Chimney

Figure 67. Anodic Gas Purification Plant Flowsheet[57]

Table 36 summarizes the removal equipment considered for emission control of the different types of effluent streams in the aluminum industry.[58]

Table 37 presents source sampling test results of a number of plants which were selected on the basis of representation of best control technology. The program included testing of potline installations at two vertical stud plants, three prebake plants, and one horizontal stud plant. A legend is given in Table 38 for the various abbreviations used.[59]

Cost data for control equipment in the primary aluminum industry are sparse, but Singmaster and Breyer have presented data derived from purchase costs reported by equipment manufacturers. Of specific interest is cost data for wet electrostatic precipitators used for control of vertical and horizontal stud cell types (shown in Figure 68).[60] It can be seen that the recent data of Bakke indicates much higher costs than the data obtained by Singmaster and Breyer.[61]

Use of Wet Precipitators for Collection of Fume from Electrolytic Reduction Cells

Martin Marietta Aluminum -

Several wet-wall precipitator units of the Mikropul design are used to collect fume from vertical spike Soderberg cells at the Dalles, Oregon. Two sizes are employed, which are capable of treating 2.83 m^3/sec (6,000 acfm) and 5.66 m^3/sec (12000 acfm). The precipitators have two plate sections in series with sprays at the entrance of each section and above the plates.

A burner is installed in the stack, but it does not remove all of the condensable hydrocarbons. A scrubber precedes the precipitator, which reportedly removes about 95% of the gaseous contaminants. Performance data from this installation, as reported by a representative of Martin Marietta to SRI personnel, is given in Table 35.

TABLE 35[64]

TYPICAL PERFORMANCE DATA OF WET PRECIPITATOR AT THE DALLES

	gr/scf	mg/m^3	Efficiency Range
Inlet	0.13-0.20	298-458	
Outlet	0.0024-0.003	5.49-6.87	97.7-98.8

TABLE 36[58]

CONTROL EQUIPMENT CONSIDERED FOR THE PRIMARY ALUMINUM INDUSTRY

	PREBAKE POTLINES			VS POTLINES		HS POTLINES		ANCILLARY PROCESSES			
	Prim. no Sec.	Sec. with Prim.	Sec. no Prim.	Prim. no Sec.	Sec. with Prim.	Prim. no Sec.	Sec. with Prim.	Bake Plant	Dry Mtls.	Paste Mix	Cast House
Burner	-	-	-	A	-	-	-	-	-	-	-
Incinerator	-	-	-	-	-	-	-	-	-	-	-
Multiple Cyclone	A	-	-	A	-	-	-	-	A	-	-
Baghouse Filter	-	-	-	-	-	-	-	-	A	-	-
Fluid Bed Dry Scrubber	A	-	-	A*	-	-	-	-	-	-	-
Coated Filter Dry Scrubber	A	-	-	-	-	-	-	-	-	-	-
Injected Alumina Dry Scrubber	A*	-	-	A*	-	-	-	-	-	-	-
Dry Electrostatic Precipitator	A	-	-	A*	-	-	-	A	A	-	-
Wet Electrostatic Precipitator	-	-	-	A	-	C	-	C	-	B	B
Spray Tower	A	-	-	A	-	A	-	A	-	A	-
Spray Screen	-	A	A	-	A	B	B	B	-	-	-
High Pressure Spray Screen	B	-	-	B	-	D	-	B	-	B	-
Wet Centrifugal Scrubber	-	-	-	D	-	-	-	-	-	-	-
Venturi	-	-	-	A	-	D	-	C	-	A	B
Chamber Scrubber	A	-	-	B	-	B	-	-	-	-	-
Wet Impingement Scrubber	-	-	-	-	-	-	-	-	-	B	-
Cross Flow Packed Bed	B	-	A	B	-	C	-	-	-	-	-
Floating Bed (Bouncing Ball)	A	-	B	A*	A*1/	A	-	B	-	D	A
Sieve Plate Tower	-	-	-	A*	-	-	-	-	-	B	-
Self-Induced Spray (Bubbler)	B	-	-	A	-	B	-	A	-	B	-
Vertical Flow Packed Bed	A	-	-	A	-	-	-	-	-	B	-

Prim. Primary collection system.
Sec. Secondary or potroom system.
A In current use in the United States.
A* In current use outside the United States.
A*1/ Used in one foreign plant. Not considered economically feasible in the United States.

B Considered feasible but not known to be in use.
C In development stage.
D Superseded by other equipment.
- Considered not feasible, economically and/or technically.

TABLE 37[59]

RESULTS OF EPA SOURCE TESTS FLUORIDE AND PARTICULATE
PRIMARY ALUMINUM INDUSTRY
lbs/Ton Aluminum *

Plant	A	A_1	A_2	B	B_1	C	D	D_1	E	F
Cell Type	VS	VS	VS	PB	PB	PB	PB	PB	HS	VS
Primary Control Device	BS-ST	BS-WESP	BS-WESP	FBDS	FBDS	ST	FBDS	FBDS	ST-WESP	ST-WESP
Secondary Control Device	SS	SS	SS	None	None	SS	None	None	None	None
PARTICULATES										
Primary Collection	NS	91.26(67.60)[2]	NS	110.10	100.30	NS	72.26	NS	81.80	38.20
Secondary Collection	-	27.12(26.68)	-	NS	NS	-	NS	-	NS	NS
Primary Emission	-	0.12(0.11)	-	13.79	1.80	-	4.00	-	5.95	1.34
Secondary Emission	-	9.53(5.83)	-	NS	NS	-	NS	-	NS	NS
Total Emission	-	9.65(5.94)	-	-	-	-	-	-	NS	NS
Primary Efficiency(%)	-	99.86(99.84)	-	87.46	98.19	-	94.43	-	92.73	96.58
Secondary Efficiency(%)	-	64.85(78.15)	-	NC	NC	-	NC	-	NC	NC
Overall Control Efficiency(%)	-	91.85(93.70)	-	-	-	-	-	-	-	-
TOTAL FLUORIDE (Particulates & Gaseous)										
Primary Collection	53.50	37.69	NS	NS	37.80(48.05)	28.10	61.40	NS	46.53	NS
Secondary Collection	3.65	3.02	NS	-	1.20	9.06	1.17	NS	2.06	-
Primary Emission	1.65	0.01	0.02	-	0.14	69.64[3]	0.87(0.49)[4]	0.35	0.41	-
Secondary Emission	1.65[1]	0.81	2.05	-	1.20	7.30	1.17	1.17	2.06	-
Total Emission	3.30	0.82	2.07	-	1.34	76.94	2.04(1.66)	1.52	2.47	-
Primary Efficiency(%)	96.91	99.97	99.94	-	99.62(99.54)	-	98.64(99.23)	99.11	99.11	-
Secondary Efficiency(%)	54.79	73.17	32.12	-	NC	19.42	NC	NC	NC	-
Overall Control Efficiency(%)	94.22	97.98	94.92	-	96.89(97.46)	-	96.89(97.46)	94.95	94.95	-

Plant	G	H
Control	ESP	ESP
ANODE BAKE PLANTS(5)		
Particulate Emissions	1.56	3.96
Total Fluoride Emissions	0.88	1.25

*Refer to legend on following page.

TABLE 38[59]

LEGEND FOR TABLES AND FIGURES

VS	Vertical stud Soderberg cell
PB	Prebake cell
HS	Horizontal stud Soderberg cell
BS	"Bubbler" scrubber
ST	Spray tower
WESP	Wet electrostatic precipitator
SS	Spray screen
FBDS	Fluid bed dry scrubber
NS	No sampling
NC	No Control
(1)	Average of two tests; one test suspected to be contaminated and deleted.
(2)	Average of two tests; one test deleted due to stud blow during test.
(3)	Samples suspected to be contaminated during sampling; these plant data are suspect.
(4)	Data with two tests deleted due to suspected control system malfunction.
(5)	Anode plant emission units are lb/ton anode produced.

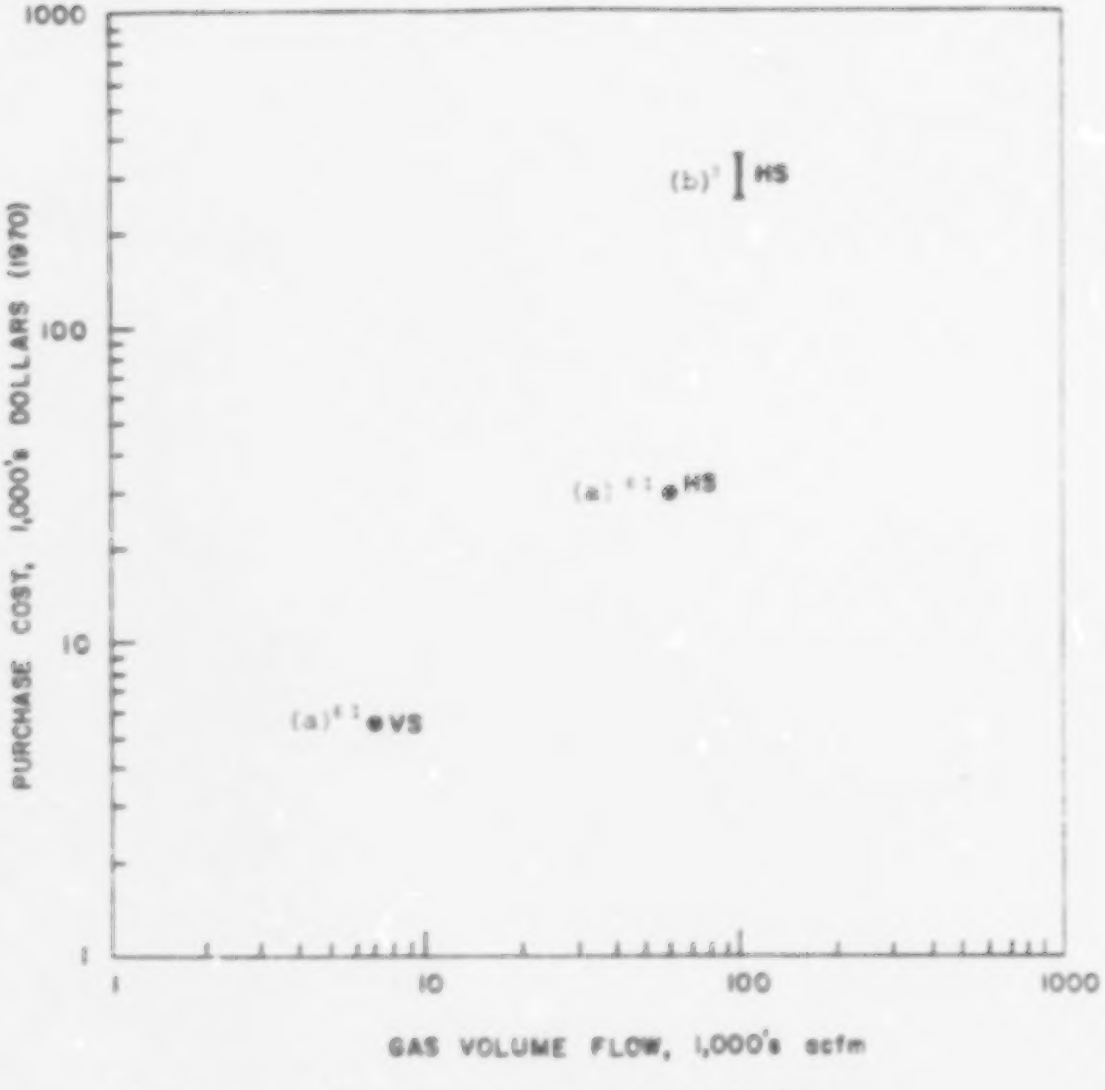


Figure 68. Cost Data for Wet Precipitators

The specific collecting area of these units, not including the exit baffles is about 53.2 $m^2/(m^3/sec)$, or 270 $ft^2/1000$ cfm. Typical electrical operating conditions are given in Table 39 The liquid to gas ratio used in the precipitator sprays was about 1.0 l of liquid per m^3 of gas (7.5 gal/1000 cf).

TABLE 39[66]

TYPICAL ELECTRICAL CONDITIONS FOR WET PRECIPITATOR AT THE DALLES

	Voltage, kV	Current Density, na/cm^2
Inlet Section	56	45.7
Outlet Section	49	56.5

The precipitator shell bottom has been replaced with fiberglass because of corrosion due to the acidic environment. Discharge electrodes and the precipitator plates are stainless steel and have held up fairly well, although there have been some problems with plate bending. Insulators have also caused some problems, but the overall down time of the precipitators was said to be less than 1%. A routine cleaning of the precipitators is performed every six weeks, and no problems with deposits have been encountered.

Plant personnel stated that local pollution control authorities were pleased with the gas effluent from the wet precipitators, which comprises only about 3% of the total particulate emissions from the plant. However, water pollution from the wet cleaning system is a problem, and some consideration is being given to a dry removal system. The pH of the discharge water from the system is about 2.5.

A similar wet precipitator installation is employed by Martin Marietta at Goldendale, Washington. Table 40 gives outlet data obtained by the State of Washington in October of 1972 at this location on the No. 1 precipitator, and Table 41 compares the wet precipitator emissions with other sources of emissions at the plant.[62]

TABLE 40[62]

EMISSION MEASUREMENTS ON ELECTROSTATIC PRECIPITATOR
NO. 1, MARTIN MARIETTA PLANT AT GOLDENDALE, WASHINGTON

	Mass Loading						Sampling Time
	Benzene Sol.		Benzene Insol.		Total		
ft^3 Sampled	mg/m^3	gr/ft^3	mg/m^3	gr/ft^3	mg/m^3	gr/ft^3	Minutes
1437	1.00	0.00044	3.02	0.00132	4.03	0.00176	222

TABLE 41[62]

SUMMARY OF MEASURED EMISSIONS

SOURCE	SAMPLING LOCATION	POLLUTANT MEASURED	CONCENTRATION	EMISSION RATE	ALLOWABLE EMISSION	EMISSION* FACTOR	METHOD
Pot room	Roof monitor	Particulate	.00063 gr/ft³	69.1 lb/hr		5.38 lb/ton	Intermediate Volume Sampler
Hoods around anode bases	Electrostatic precipitator	Particulate	.00176 gr/ft³	2.54 lb/hr		.20 lb/ton	
Pot room	Roof monitor	Extracted Particulate	.00026 gr/ft³	28.5 lb/hr	15 lb/ton total	2.22 lb/ton	Intermediate Volume Sampler (benzene extract)
Hoods around anode bases	Electrostatic Precipitator	Extracted Particulate	.00132 gr/ft³	1.91 lb/hr		.15 lb/ton	
Pot room	Roof monitor	Fluorides (as HF)	283 µg/m³	10.15 lb/hr	To meet WAC 18-48 ambient & forage standard	.79 lb/ton	NaOH absorption & specific ion electrode
Hoods around anode bases	Electrostatic Precipitator	Fluorides (as HF)	96 µg/m³	.62 lb/hr		.05 lb/ton	
Hoods around anode bases	Electrostatic Precipitator	SO_2	26 ppm	47.6 lb/hr		3.65 lb/ton	NaOH absorption & turbidometric
Pot room	Roof monitor Line B, Sec. 1	CO	24 ppm	1496 lb/hr		117 lb/ton	Grab sample & non-dispersive infra-red
Hoods around anode bases	Electrostatic Precipitator No. 1	CO	12750 ppm	9523 lb/hr		742 lb/ton	
Pot room	Roof monitor Line B, Sec. 1	Hydrocarbons (as CH_4)	6 ppm	214 lb/hr		16.7 lb/ton	Grab sample & flame ionization
Hoods around anode bases	Electrostatic Precipitator No. 1	Hydrocarbons	75 ppm	32 lb/hr		2.5 lb/ton	
Pot room	Roof monitor	3 - 4 Benzopyrene	158 Nanograms/M³	.0083 lb/hr		.00065 lb/ton	I.V. Sampler + Benzene Extraction + Adsorption Chromatography + Colorimetric

* Based on average daily production of 308 tons aluminum

SECTION VIII

SUMMARY OF STATUS OF WESP TECHNOLOGY AND DESIGN METHODS

Wet electrostatic precipitators have been effectively used to collect particulate matter in the aluminum, iron and steel, chemical, and petrochemical industries. Duct-type collecting electrodes are generally used for the applications in which relatively large gas volumes are to be cleaned. The advantages of plate electrodes as opposed to pipe electrodes are less expensive construction and the flexibility of allowing variations in electrical sectionalization. Pipe electrodes can be more uniformly irrigated than plates, and gas by-passage (sneakage) is not a factor. Saturation of the gas stream with water prior to entering a WESP is desirable with all electrode geometries to prevent deposit formation and to maximize effective utilization of the precipitation process for removing particles.

The largest recent application of WESPs has been in the collection of fume from aluminum pot lines. A field test of a full scale duct-type wet ESP installed on an aluminum pot line indicated that collection efficiencies of 95 to 98% were achieved on a particle size distribution in which about 65% of the mass consisted of sub-micron particles. The specific collection area during the test period was approximately 62 $m^2/(m^3/sec)$. Corrosion and deposit formation in the liquor supply system have occurred at this installation.

In the iron and steel industry, WESPs are used on electric arc furnaces, blast furnaces, basic oxygen furnaces, scarfers, and cupolas. In some of the electric arc furnace WESP installations, intermittent washing of the plate-type electrodes was found to be preferable to continuous irrigation. These units have either two or three fields in series, and the field undergoing washing is de-energized during the washing period. This is in contrast to the aluminum pot line installations, which employ continuous irrigation. Wet precipitators of the wire and pipe design have been widely used for cleaning blast furnace gas, but this is a declining application area because of the recent trend toward the use of blast furnaces with high top pressures. The energy available with the high pressures can be utilized in high energy particulate scrubbers with a lower capital investment compared to precipitators.

Electrostatic precipitators are used as collectors of tars and oils in the steel and petrochemical industry, and for collection of acid mists from sulfuric and phosphoric acid production in the chemical industry. These types of units do not usually employ forced irrigation of the collecting electrodes, but they are "wet" in the sense that collected material is a fluid, and no electrode rapping is employed. Detarring ESPs are typically of the wire and pipe design, with the pipes suspended from a header plate in a round shell. Acid mist precipitators are also typically of the wire in tube type, but the wire and plate design is common in Europe.

Design methods for sizing wet electrostatic precipitators have included pilot plant studies and design by analogy based on the empirical application of the Deutsch equation with a "precipitation rate parameter" used as an indicator of performance. For the blast furnace and sulfuric acid mist applications, the data in the literature concerning design versus installed performance is reported as the term (R) which is the ratio of the precipitation rate parameter obtained from test data to that used in designing the unit. For example, a value of R of 1.20 means that the precipitator plate area is 20% larger than required to meet the design efficiency for that particular unit. The scatter in the R values (typical range, .5 to 1.5) indicates the need for more precise sizing methods.

The agreement obtained between the laboratory data and the predictions of the mathematical model (Section III) suggests that the mathematical model offers a tool which can be used to estimate plate area requirements for various wet precipitator application areas. The computer model in its present state of development is useful for qualitatively predicting performance trends caused by changes in specific collecting area, electrical conditions, and particle size distributions. Current density, applied voltage, and the particle size distribution are the most important variables in the calculation of overall mass collection efficiency for a given specific collection area. A detailed discussion of the mathematical model is given in Reference 1.

ACKNOWLEDGMENTS

The design of the wet precipitator was performed by Mr. Norman H. Francis, Research Engineer, and the laboratory-experimental work was performed by Mr. Leon B. Hill, Research Technician. The European visits were conducted by Dr. Charles E. Bates, Head of the Metallurgy Section.

SECTION X

REFERENCES

1. Gooch, J., J. McDonald, and S. Oglesby, Jr. A Mathematical Model Of Electrostatic Precipitation. Southern Research Institute, Birmingham, Alabama. Contract No. 68-02-0265. The Environmental Protection Agency, Research Triangle Park, North Carolina. April 1975.

2. Gooch, J. and J. McCain. Particulate Collection Efficiency Measurements On A Wet Electrostatic Precipitator. Southern Research Institute, Birmingham, Alabama. Contract No. 68-02-1308. The Environmental Protection Agency, Research Triangle Park, North Carolina. March 1975.

3. Bakke, Even. The Application of Wet Electrostatic Precipitators For Control Of Fine Particulate Matter. Paper presented at the Symposium on Control of Fine Particulate Emissions from Industrial Sources for the Joint U.S.-U.S.S.R. Working Group, Stationary Source Air Pollution Technology. San Francisco, California, January 15-18, 1974.

4. Oglesby, S. and G. Nichols. A Manual of Electrostatic Precipitator Technology. Part II - Application Areas. Prepared under Contract CPA 22-69-73 for NAPCA. Southern Research Institute, Birmingham, Alabama. August 25, 1970.

5. Faust, et al. Principles of Unit Operations. New York, John Wiley & Sons, 1960. p. 170.

6. Gooch, J. and J. McDonald, op. cit.

7. Epstein, Michael. EPA Alkali Scrubbing Test Facility: Summary of Testing through October 1974. Report to U.S. E.P.A., Contract No. PH 22-68-67. Bechtel Corporation. San Francisco, California. June 1975.

8. Droplet Measurements at the Colbert Scrubber Pilot Plant Performed by KLD Associates, Inc. KLD Technical Memorandum No. 14. August 1974.

9. Ensor, et al. Evaluation Of A Particulate Scrubber On A Coal-Fired Utility Boiler. Meteorology Research, Inc., Altadena, California. Contract No. 68-02-1802. The Environmental Protection Agency, Research Triangle Park, North Carolina. November 1975.

10. Calvert, S., J. Goldshmid, D. Leith, and D. Mehta. Scrubber Handbook. Ambient Purification Technology. Riverside, California.

11. United States Steel. The Making, Shaping, and Treating of Steel, McGannon, Harold E. (ed.). 8th Edition, 1964.

12. Oglesby, S. and G. Nichols, op. cit.

13. Uys, J. and J. Kirkpatrick. The Beneficiation of Raw Material in the Steel Industry and Its Effect Upon Air Pollution Control. J. Air Pollut. Control Assoc. 13: 20-27, January 1963.

14. Varga, J. and H. Lownie. Final Technological Report on A System Analysis Study of the Integrated Iron and Steel Industry, to Division of Process Control Engineering, NAPCA, from Battelle Memorial Institute. May 15, 1969.

15. Bishop, C. A. Metallurgical Furnace Stacks. AIHA Quarterly 11:34-39, March 1950.

16. Oglesby, S. and G. Nichols, op. cit.

17. Oglesby, S. and G. Nichols, op. cit.

18. Spreux, M. and L. Gagnaire. The Dust Extraction Equipment at the Usinor-Dunkirk (France) Steelplant. Translated from Revue de Metallurgi 60(11):1103-10, 1963.

19. Scheidel, K. Electrical Gas Cleaning in Heavy Industry. Metallyesellschaft Mitteilungen (Metallgesellschaft Review of the Activities), no. 4, 33-44, 1962.

20. Otsubo, S., et al. Operation of Newly Installed Lurgi Venturion Type Blast Furnace Gas Precipitator. Seitetsu Kenkyu, no. 249, 148-155, December 1964.

21. Speight, G. Air Pollution Control in the British Iron and Steel Industry. Steel Times 200:395-402,407, May 1972.

22. American Iron and Steel Institute, Annual Statistical Report, 1970.

23. Walters, C. Air Pollution Control for the Metals Industry. Republic Steel Corporation. June 4, 1968.

24. Oglesby, S. and G. Nichols, op cit.

25. Systems Analysis of the Integrated Iron and Steel Industry. Report to Battelle Memorial Institute by Swindell-Dressler Company, Pittsburgh, Pennsylvania. NAPCA Contract PH 22-68-65. March 31, 1969.

26. Oglesby, S. and G. Nichols, op. cit.

27. ibid.

28. Muhlrad, W. Dust Extraction from the Fume of Electric Arc Furnaces. Iron and Coal 183:669-675, 1961.

29. Davis, C. Gas and Liquid Filtration in the Steel Industry. Filtration Separation 8(4):418-424, July/August 1971.

30. Holland, M. and K. Whitwam. Direct Fume Extraction for Large Arc Furnaces, Fume Arrestment Spec. Report 53, William Lea and Co. 1964. p. 150-159.

31. Fraunfelder, A. New Development in Cleaning Equipment for Fumes Emanating from Ferrosilicon Electric Furnaces. Tidsskrift for Kjerni Bergvesen Metallurgi 23:110-114, May 1963.

32. Fraunfelder, A. Experience Gained with a New Scrubber-Precipitator Combination. Krupp Technical Review 22(3):125-126, 1964.

33. Elliott, A. and A. Lafreniere. The Design and Operation of a Wet Electrostatic Precipitator to Control Billet Scarfing Emissions. Paper #71-159 presented at the 64th Annual Meeting of the Air Pollution Control Association, Atlantic City, N.J., June 27-July 2, 1971.

34. Engels, G. and E. Weber. Cupola Emission Control. Translation, P. S. Cowen (ed.). Cleveland, Ohio, Gray and Ductile Iron Founders' Society, 1967.

35. Engels, G. and E. Weber, op. cit.

36. Ussleber, K. Design of Hot Blast Cupola Plant With a Wet Electrostatic Precipitator for Cleaning the Stack Gas. Translated from Giesserei 52(7):194-197, 1965.

37. Oglesby, S. and G. Nichols, op. cit.

38. Brown, R. F. A Report on the Use of Electrostatic Precipitators in the Iron and Steel Industry. Research-Cottrell, Inc., Bound Brook, N.J. February 10, 1970.

39. Frisch, N. W. A Report on the Use of Electrostatic Precipitators in the Chemical Process Industries. Research-Cottrell, Inc., Bound Brook, N.J., February 24, 1970.

40. Cree, K. H. Cottrell Electrical Precipitation as Applied to the Manufactured Gas Industry. Am. Gas J. 162:27, March 1945.

41. Francombe, K. W. Electro-Detarring. Trans. Inst. Gas Eng. 99:132-195, 1949-1950.

42. Shreve, R. Norris. Chemical Process Industries, 3rd Edition. New York, McGraw-Hill Book Co., 1967. p. 329-330.

43. Compilation of Air Pollution Emission Factors, 2nd Edition. U.S. Environmental Protection Agency, Research Triangle Park, N.C., April 1973.

44. Gillespie, G. R. Particle Size Distribution in Hygroscopic Aerosols. Engineering Experiment Station, University of Illinois, Urbana, Illinois. May 1, 1953.

45. Air Pollution Engineering Manual, 2nd Edition. John A. Danielson (ed.). Air Pollution Control District, County of Los Angeles, May 1973.

46. Frisch, N. W., op. cit.

47. Atmospheric Emissions from Thermal-Process Phosphoric Acid Manufacture, Cooperative Study Project, Manufacturing Chemists' Association, Inc., and Public Health Service, NAPCA Publication No. AP-48, October 1968, p. 11. Superintendent of Documents, U. S. Government Printing Office, Washington, D.C.

48. Brink, J. A. and C. E. Contant. Experiments on an Industrial Venturi Scrubber. Ind. Eng. Chem. 50:1157-60, August 1958.

49. Brink, J. A. Removal of Phosphoric Acid Mists. In: Processes for Air Pollution Control, 2nd Edition, G. Nonhebel (ed.). Cleveland, Ohio, CRC Press, 1972. p. 557.

50. Jones, H. R. Pollution Control in the Nonferrous Metals Industry. Noyes Data Corp., Park Ridge, N.J., 1972. p. 12,14.

51. MRI. Particulate Pollutant System Study. Vol. III - Handbook of Emission Properties, May 1, 1971. p. 287.

52. Singmaster and Breyer. Air Pollution Control in the Primary Aluminum Industry, Vol. I, Sec. 3. July 23, 1973. p. 11.

53. Ibid, p. 15.

54. Ibid, p. 14.

55. Ibid, Sec. 4, p. 6.

56. Hanna, Thomas and Michael Pilat. Size Distribution of Particulates Emitted from a Horizontal Spike Soderberg Aluminum Reduction Cell. J. Air Pollut. Control Assoc. 22:536, July 1972.

57. Callaioli, G., U. Lecis, and R. Morea. Systems of Gas Collection and Cleaning in Electrolytic Furnaces of Montecatini Edison Aluminum Plants. Paper A70-23, Institute for Iron and Steel Studies, 1970 Offshore Technology Conference.

58. Singmaster and Breyer, op. cit., p. 13.

59. Ibid, p. 20-21.

60. Ibid, p. 5.

61. Op. cit.

62. Washington State Dept. of Ecology, Report No. 72-28, Source Test, Summary of Emissions to Atmosphere. November 21, 1972.

63. Sui, C.T. A Report on the Use of Electrostatic Precipitators in the Petroleum Refining Industry. Research-Cottrell, Inc., Bound Brook, N.J., February 13, 1970.

64. Personal Communication with Martin Marietta.

SECTION XI

APPENDIX A

CONVERTING UNITS OF MEASURE

To Convert From	To	Multiply By
lbs	kg	0.454
grains/cf	grams/m^3	2.29
cfm	m^3/sec	0.000472
lbs/in.^{2}	kg/m^2	703
°F	°C	(F - 32) x 5/9
ft^2/1000 cfm	$m^2/(m^3/sec)$	0.197
inches w.g.	mm Hg	1.868
gallon	liter	3.785
ft	m	0.3048
inches	m	0.0254
tons	kg	908
cubic inches	cubic centimeters	16.39
cubic feet	cubic meters	0.028
cubic feet	liters	28.32
gallon/minute	liters/second	0.0631
square feet	square meters	0.0929
square inches	square centimeters	6.452
gallon/1000 ft^3	liters/m^3	0.135
grams	grains	15.43

APPENDIX B

LITERATURE STUDY BIBLIOGRAPHY

FUNDAMENTAL INFORMATION

Tuma, Jiri. Dust Properties Which Affect Separation. Staub. 26(11):1-6, 1966.

Liu, Benjamin, and Yeh, Hsu-Chi. On the Theory of Charging of Aerosol Particles in an Electric Field. Journal of Applied Physics. 39(3):1396-1402, February 1968.

Glowiak, Bohdan, and Kabsch, Piotr. Method for Determination of the Wettability of Dusts and Importance of the Investigation Results for Practical Use. Staub. 32(1):12-15, January 1972.

Hanson, D. N. and Wilke, C. R. Electrostatic Precipitator Analysis. Industrial and Engineering Chemistry, Process Design and Development. 8(3):357-364, July 1969.

Masuda, S. I., Onishi, Toshio, and Saito, Hiroshi. Inlet-Gas Humidification System for an Electrostatic Precipitator. Ind. Eng. Chem. Process Design Develop. 5(2):135-45, April 1966.

Richards, Clyde. Distortion and Instability of Electrically Stressed Water Drops Falling at Terminal Velocity. Dissertation Abstracts-B. 32, June 1972.

Darby, K. The Use of Electrostatic Forces for the Separation of Suspended Materials in Liquids and Gases. Lodge-Cottrell Limited, Birmingham, England.

Frauenfelder, A. Overcoming Special Problems in Electrical Precipitation. Filtration Society's Conference on What's New in Dust Control and Air Cleaning at the Dust Control and Air Cleaning Exhibition, Olympia, London. September 25-27, 1973.

Schütz, Alfred. The Electrical Charging of Aerosols. Staub. 27(12):24-32, December 1967.

PATENTS

Revell, A. and Welch, W. Gas Filter Apparatus. U.S. Patent #3,505,786. April 14, 1970.

Meston, A. F. Downdraft Wet Precipitator. Patent #1,239,844. February 3, 1920.

Masuda, S. Apparatus for Electrostatic Precipitation of Dust. U.W. Patent #3,444,668. May 20, 1969.

PATENTS (Cont)

Schmidt, W. A. Process and Apparatus for Collecting Suspended Material from Furnace Gases. Patent #1,413,877. April 25, 1922.

Cottrell, F. G. Purification of Gases. Patent #1,016,476. February 6, 1912.

Wolcott, E. R. Method for the Removal of Suspended Material from Gases. Patent #1,479,270. January 1, 1924.

Finney, J. A. Electrode Configuration in an Electrical Precipitator. Patent #3,570,218. March 16, 1971.

Hodson, P. and Klemperer, H. Liquid Cleaned Precipitator. Patent #2,615,530. October 28, 1952.

Lenehan, Joseph W. Collecting Electrode Structure. Patent #2,853,150. September 23, 1958.

Gustafsson, S. and Öhnfeldt, P. Method for Cleaning the Electrodes in Electro-filters. Patent #2,874,802. February 1959.

Hedberg, C. W. J. Collection of Suspended Particles. Patent #2,677,439. May 4, 1954.

Bradley, L. Apparatus for Separating Tar from Gases. Patent #1,473,800. November 13, 1923.

Vicard, P.G. Process and Apparatus for the Purification of Gases. Patent #2,983,332. May 9, 1961.

Wiemer, J. Wet Electrostatic Precipitator. Patent #3,221,475. December 7, 1965.

Ebert, P. Gas Cleaning Apparatus and More Particularly to an Improved Electrical Precipitator. Patent #3,492,790. February 3, 1970.

Penney, G.W. Electrical Dust Precipitator Utilizing Liquid Sprays. Patent #2,357,355. September 5, 1944.

Procedure for Electrical Cleaning of Gas Containing Dust with the Aid of a Wet Electrostatic Precipitator Having Plate, Wire, or Tube Electrodes. Patent #904,334 (France) Zschocke-Werke Company. February 26, 1945.

Mullin, D. D. Electrostatic Precipitator. Patent #3,444,667. May 20, 1969.

Watanabe, Y. and Nishikawa, T. Purification Device for Heated Gas. (Japan) Patent Sho 48-11550. April 13, 1973.

MIST COLLECTION

Adrain, Robert C. Two-Stage Electrical Precipitators. Air Pollution Engineering Manual. Danielson, J.A. (comp. and ed.). Cincinnati, Ohio, Public Health Service, National Center for Air Pollution Control, PHS-PUB-999-AP-40, 1967. p. 156-166.

Donovan, J. R. and Stuber, P. J. Sulfuric Acid Production from Ore Roaster Gases. Journal of Metals. November 1967. p. 45-50.

Semrau, Konrad T. Control of Sulfur Oxide Emissions from Primary Copper, Lead, and Zinc Smelters - A Review. (Paper 70-97 presented at the 63rd Annual Meeting of the Air Pollution Control Association. St. Louis, Missouri. June 14-18, 1970.)

Electrostatic Fume Collector. Staub. 34(3):102. March 1974. Handte and Company.

Electronic Air Cleaners Whisk Away Texturing Plants' Oil Mist Smoke. Textile World. 124(9):207. September 1974.

Tiesler, H. The Reduction of Odor Emissions Through Aerosol Formation and Electrostatic Precipitation. Schriftenrihe Ver. Wasser-Boden-Lufthyg (Berlin). (35):71-77. 1971.

Kubyshev, N., Krotuv, N., and Meysner, R. Production of Sulfuric Acid in Lead Factories. Tsvetnye Metally. (Moscow) (10):22-25. October 1972.

Dougill, G. Cleaning of Producer Gas. Transactions Institute Chemical Engineers. 23:230-3nd. 1945.

Pexton, S., Dougill, G., and Ravald, L. Removal of Tar, Naphthalene, and Amonia from Gas. Gas Journal. 254:539-544. June 9, 1948.

Beltran, M. Smoke Abatement for the Carpet Industry. Carpet and Rug Industry. May 1973.

Beltran, M. Smoke Abatement for Textile Finishers. American Dyestuff Reporter. August 1973. p. 26-31.

Willett, H. Cleaning, Cooling, and Drying of Gases. Manufacture of Sulfuric Acid. J. Duecker. 1959.

Lilley, J. N. Handling of Acid Slurries at the Flash Smelting Plant of the International Nickel Company of Canada. Canadian Mining Mettalurgical Bulletin. 54(589), May 1961.

Niimura, M., Konada, T., and Kojima, R. Sulfur Recovery from Green-Charged Reverberatory Off-Gas at Onahama Copper Smelter. (TMS Paper No. A73-47, The Metallurgical Society of AIME, N.Y.

MIST COLLECTION (Cont)

Hensinger, C.E., Wakefield, R.E., and Claus, K.E. Turning Pollution Gases into Profits. Eng. Mining J. 169:131-135, February 1968.

Hensinger, C.E. and Wakefield, R.E. New Roasters Spur Production of Sulfuric Acid and Zinc Oxide Pellets. Chem. Engineering. June 1968. p 70-73.

Beals, G.C. and Cadle, J.J. Copper and By-Product Sulfuric Acid Production by Palabora Mining Company. Journal of Metals. July 1968. p 85-90.

Cree, K. H. Cottrell Electrical Precipitation as Applied to the Manufactured Gas Industry. Amercian Gas Journal. 162:27-30, March 1945.

Manufacturing Chem. Assoc. Inc. and Public Health Service, U.S. Dept. of HEW. Atmospheric Emissions from Thermal-Process Phosphoric Acid Manufacture, 1965.

Ross, W.H., Carothers, J. N., and Merz, A.R. Use of Cottrell Precipitator in Recovering H_3PO_4 Evolved in Volatilization Method of Treating Phosphate Rock. Journal of Industrial Engineering Chemistry. 9(1):26-31, June 1917

Allgood, R. W. Sulfuric Acid and Liquid Sulfur Dioxide Manufactured from Smelter Gases at Copper Cliff, Ontario. Canadian Mining Metallurgical Bulletin. 45(497):153-155, March 1952.

Mills, John L., Kallan, Leo E., Lemke, Eric E., and MacKnight, Robert J. Unique Applications of Air Pollution Control Devices. (49th Annual Metting of APCA. Buffalo, New York. May 20-24, 1956.) p 11-1 - 11-20.

Apakhov, I. A., Inyushkin, N. V., Kravchenko, E. A., Bulycheva, L. I., Shakhov, G. F., Goncharov, A. Ye., Chemenov, A. N., and Usov, G. A. Scrubbing of Sulfuric Acid Mist with the Aid of Industrial Electrofilters. Khim. Pro. (Moscow) 9:676-678,1972.

Staschik, Guenter. Separation of Plasticizer Mists in the Processing of PVC Mixtures. Kunststoffe. 59(7):416-418, 1969.

Kitani, R., Kubo, Y., and Otsuka, H. Anti-Acid Refractory Mist Cottrell. Jap. Pat. SHO 47-28609, July 1972.

Roll, Kempton H. Controlling Corrosive Air Pollutants. Journal Air Pollution Control Association. 1(6):6-10, May 1952.

MIST COLLECTION (Cont)

Bronsard, Joseph A. and Toro, Richard F. Odor Control of Paper Recycling. Pollut. Eng. 4(5):18-19, August 1972.

Cotham, R.L. Electrostatic Precipitation of Sulfuric Acid Mists. Proc. Clean Air Conf. University of New South Wales, Paper 20. 2, 1962.

Faith, W.L. Air Pollution Abatement...Survey of Current Practices and Costs. Chemical Engineering Progress. 55(3):38-43, March 1959.

Thompson, R. and Butler, E. History of Sulfuric Acid Production from Converter Gas at the Kennecott Copper Corporation's Utah Smelter. Journal of Metals. 20(7):32-34, July 1968.

Plastics Industry Ponders its Recycling Problems. Chemical Engineering. 78(12):56, June 1973.

Manufacturing Chemists Association, Inc., and Public Health Service. Atmospheric Emissions from Sulfuric Acid Manufacturing Processes. U.S. Dept. of Health, Education, and Welfare, 1965.

McBreen, J.P. Electric Detarrers for Gasworks. Metropolitan-Vickers Gazette. 22:238-240, February 1948.

Quitter, Volker. Electrostatic Separation of SO_3 Mists. Staub. 30(4):8010, April 1970.

Ochs, H. The Purification of Recirculated Air in Rolling Operations. Metall. 4:348-351, 1965.

Brink, J.A. Mist Removal - Removal of Phosphoric Acid Mists in Processes Air Pollution Control, Nonhebel, G. (ed). Cleveland, CRC Press, 1972. p 549-563.

Stastny, E.P. Electrostatic Precipitation. Chemical Engineering Progress. 62(4):47-50, April 1966.

Sykes, W. and Broomhead, F. Problems of Electrical Precipitation Reviewed. Gas World. 134(3494):98-104, August 1951.

Francombe, K.W. Electro-Detarring. Transactions Institute of Gas Engineer. 99:132-195, 1949-50.

Jepoon, J. Electrostatic Precipitators for Reformed Gas. Gas Journal. 317:224-227, February 1964.

Westh, H. C. Electrostatic Precipitators. Trans. Ingeniøren (Copenhagen). 58(1):36-48, 1949.

MIST COLLECTIONS (Cont)

Goncharov, A. Y. E. and Fedotov, M. V. Intensified Process for the Removal of Sulfuric Acid Mist from Gases by Electrostatic Technique. Khim. Prom., No. 4. 1973. p 49-51.

Ochs, Hans-Joachim. Precipitation of Oil Mists with Electrostatic Precipitators. Energie Tech. 23(1):9012, January 1971.

Grootenhuis, B. J. Small-Scale Electrostatic Precipitator. Chem. and Process Eng. 48(2):101, February 1967.

Norman, G. H. C. Electrostatic Precipitation. Can. Mining Journal. 91(10):69-71, October 1970.

Stopperka, Klaus. Electroprecipitation of Sulfuric Acid Mists from the Waste Gas of a Sulfuric Acid Production Plant. Staub. 25(11):70-4, November 1965.

Goldfield, J. and McAnlis, R. Low-Voltage Electrostatic Precipitators to Collect Oil Mists from Roofing Felt Asphalt Saturators and Stills. Amer. Ind. Hygiene J. 24(4):411-416, 1963.

Wet Electrostatic Precipitator Tames Oils, Gases and Fires. Chem. Eng. July 1973. p 74-76.

Asarco Dedicates Hayden Acid Plant. Mining Congr. J. 58(3):28-29, March 1972.

Fairs, Lowrie G. Removal of Acid Mists from Chemical Processes. Processes Air Pollution Control (Eng.) 1972. p 520-49.

Rodolff, D. W. and Marble, E.R. Jr. Inspiration's New Look. J Metals. 29(7):14-24, July 1972.

IRON AND STEEL INDUSTRY

Johnson, D. Air Pollution Practice in the UK Steelmaking Industry. Iron and Steel (London). 44(6):463-466, December 1971.

Dust Removal from Fumes Emitted by The Valmoesa Electrometallurgical Plant (Switzerland). J. Four Elec. (3):75-81, March 1969.

Arimitsu, T. Dust Prevention at Iron Manufacturing Factory, Proc. Assoc. Prev. Ind. Pub. Niusance Symp., 2nd. Japan, October 3-7, 1972.

Lindau, L. and Schweitz, L. Air Pollution from Cupolas, Statens Naturvardsverk (Stockholm), 1968.

Engels, G. Present Status of Dust Control for the Cupola in the German Federal Republic; Results of the V.D.G. Questionnaire in 1963. Giesserei. 51:68-73, February, 1964.

IRON AND STEEL INDUSTRY (Cont)

Restricting Dust Emission in Blast Furnace Operation. Society of German Metallurgists (Dusseldorf). VDI No. 2099, February 1959.

O'Mara, R. F. Dust and Fume Problems in the Iron and Steel Industry. Iron and Steel Engineer. October 1953. p 100-106.

Smith, Jack. Coast's Largest Steel Plant Keeps Air Clean. Air Engineering. 1:21-24, November 1959.

Heinrich, R. F. Special Applications of the Electrical Gas Cleaning Procedures. Ver. Deut. Ingr. (Duesseldorf). 98(28): 1633-1638, October 1956.

Guthmann, Von Kurt. Development of Blast Furnace Gas Cleaning in the Last Ten Years. Stahl and Eisen. 73(5):283-291, February 1953.

Howell, G. A. Air Pollution Control in the Steel Industry. Iron and Steel Engineer. October 1953. p 91-94.

Merkel, Christian, and Guelland, Joachim. Some Dust Collection Problems in the Steel Industry. Neue Hüette. 17(5):257-260, May 1972.

Tanigushi, Akira and Kamoshida, Shuichi. A New Electric Dust Collector. Jap. Pat. SHO 45-28478.

O'Mara, Richard and Flodin, Carl R. Electrostatic Precipitation as Applied to the Cleaning of Gray Iron Cupola Gases. Air Repair. 3(2):105-108, November 1953.

Hashimoto, Kiyotaka. The Point of Planning and Its Effect on Operation of an Electric Precipitator in Various Industry Smoke Abatement (IV) - Treatment for Waste Gas of Iron and Steel Industry. Journal of Pollution Control. 3(2):93-012, February 1967.

Punch, G. Gas Cleaning in the Iron and Steel Industry - Part II: Applications in Fume Arrestment. Iron and Steel Inst., London (England). SR-83, 1963. p 10-23.

Renwanz, Roger A. and Specht, Schaeffer, E. Survey of Smoke Control, Part I. Steel. 135(21), November 1954.

Ueda, Akiyoshi. Precipitation of Blast Furnace. Chem. Eng. 35(1):47-53, January 1971.

IRON AND STEEL INDUSTRY (Cont)

Otsubo, S., Sanuki, Y., Yamamoto, T., Nakazono, I., and Haruta, M. Operation of Newly Installed Lurgi Venturion Type Blast Furnace Gas Precipitator. Seitetsu Kenkyu, No. 249. December 1964. p 148-155.

Guthmann, K. Cupola Gas Cleaning - Blast Furnace Gas. Giesserei. 42(19):519-524, 1955.

Guthmann, K. Emission of Dust and Gases in Iron Works and Iron Foundries. VDI Berichte. 53:46-50, 1961.

Review of the International Fair - Dust Collectors. Staub. 28(10):33-36, October 1968.

Engels, G. German Foundry Experience in Cupola Dust Emission and Emission Control. Transactions of the American Foundryman's Society. 78:287-292, 1970.

Dust Collecting Devices for Cupolas. Air Conservation. 4(2):61-63, 1970.

Fraunfelder, A. Experience Gained with a New Scrubber-Precipitator Combination. Krapp Technical Review. 22(3):125-126, 1964.

Mulrad, W. Dust Extraction from the Fume of Electric Arc Furnaces. Iron and Coal. 183:669-675, 1961.

Jennings, R. F. Blast Furnace Gas Cleaning - An Analysis of Plant Performance. Journal of the Iron and Steel Institute. 164:305-324, March 1950.

SO_2 Control Pilot Plant. Iron and Steel Engineer. November 1973. p 100

Rice, Owen R. Blast Furnace Gas Conditioning. Iron and Steel Engineer. 19(2):66-89, December 1942.

Burks, G. P. Modern Blast Furnace Gas Cleaning Practices. Journal of Metals. 188:746-750, May 1950.

Meinshausen, G. Operation Experience with Oxygen Steelworks' Fume Arrestment Equipment. Stahl and Eisen. 87(22):1304-1309, November 1967.

Meister, W. Dedusting of the Brown Fumes of a Bessemer Converter with a Wet Electrostatic Precipitator. Stahl and Eisen. 80(24): 1803-1805, November 1960.

IRON AND STEEL INDUSTRY (Cont)

Guthmann, K. New Knowledge and Experience in the Purification of Air in Metallurgical Plants. Radex-Rundschau. (3):139-162, June 1966.

Meister, W. and Koglin, W. Clean Air and the Steel Industry. Arbeitsschutz. 6:138-140, 1960.

Bothe, R. New Methods in Electrostatic Dedusting of Waste Gases with High CO Content Coming from Steel Works Converters. Second International Congress on the International Union of Air Pollution Prevention Association. Washington. Paper EN-34D. December 6-11, 1970.

Werner, H. Questions of Dedusting in Foundries with Special Attention to the Adding of Electrofilters. Klepzig Fachber. 72:392-396, October, 1964.

Höhle, Leonhard. Use of Disintegrators for Cupola Dust Removal. Giesserei. 58:357-632, June 1971.

Speight, G. E. Air Pollution Control in the British Iron and Steel Industry. Steel Times. 200:395-402, 407, May 1972.

Spreux, M. and Gagnaire, L. The Dust Extraction Equipment at the Usinor-Dunkirk (France) Steelplant. Trans. Revue de Metallurgie. 60(11):1103-10, 1963.

Holland, M. and Whitman, K. Direct Fume Extraction for Large Arc Furnaces. Fume Arrestment Spec. Report 83. William Lea & Co. 1964. p 150-159.

Frauenfelder, A. New Development in Cleaning Equipment for Fumes Emanating from Ferrosilicon Electric Furnaces. Tidsskrift for Kjemi Bergvesen Metallurgi. 23(5):110-114, May 1963.

Bruederle, E., Scheidel, C., and Werner, H. Electro-Precipitators in the European Iron and Steel Industry. Blast Furnace and Steel Plant. 38:1031-1037, October 1960.

Hipkin, A. S. Arc Furnace Fume Cleaning. Conference on the Control and Collection of Fume from Steel Foundry Melting Furnaces by B.S.C.R.A. New York. April 1963. p 77-82.

Scheidel, K. Industrial Gas Cleaning by Electroprecipitation. Metallgesellschaft Review of the Activities. (4):33-44, 1962.

O'Mara, R. F. Dust and Fume Problems in the Steel Industry. Engineer's Digest. 14(12):456-459, 470, December 1953.

Vacek, A. and Schertler, A. Waste Gas Cleaning Systems of Oxygen and Steel Plants. Iron and Steel Institute. 71:82-89, 1957.

IRON AND STEEL INDUSTRY (Cont)

Richardson, H. L. The Role of Electrical Precipitation in the Steel Industry. Iron and Steel Engineer. 30(10):95-100, October 1953.

Shaw, F. M. Iron Foundry Air Pollution in the United Kingdom. British Foundryman. 65(3):90-105, March 1972.

Organization for Economic Co-operation and Development. Air Pollution in the Iron and Steel Industry. McGraw Hill, New York, 1963.

Poetschke, Herbert. Dust Collection and Combustion. Wasser Luft Betrieb. 17(3), 1973.

Fume Control on the Electric Arc Furnace. British Steelmaker. 37(8):20-21, 23-24, August 1971.

Davis, C. M., and Coles, R. R. Gas and Liquid Filtration Separation. 8(4):418-424, July/August 1971.

Singhal, R. K. Fume Cleaning Systems Used in the Steel Industry - Part I. Steel Times (London). 197(8):531-538, August, 1969.

Esser, Karol. Design Requirements for Industrial Plants with Air-Polluting Emission. Staub. 25(1):2-5, January 1965.

Engels, G. Some German Experiences with Cupola Dust Extraction Plants Using Various Systems - Part II. Geisserei. 52(2):33-37, January 1965.

Liesegang, Dietrich. Wet Separators for Cleaning Cupola Furnace Gases. Geisserei. 58(12):1-15, June 1971.

Ussleber, K. Design of a Hot-Blast Cupola Plant with a Wet Electrostatic Precipitator for Cleaning the Stack Gas. Giesserei. 52(7):194-197, 1965.

Misaki, Haruo. Removal of Sulfur from Flue Gases by the Double Contact Process. Fuel and Combustion. 38(4):314-321, 1971.

Schnitzler, Herman. Further Tests with a New Electrostatic Precipitator. Staub. 25(3):43-45, March 1965.

Elliott, A. C. and Lafreniere, A. J. The Design and Operation of a Wet Electrostatic Precipitator to Control Billet Scarfing Emission. (Presented at 64th Annual Meeting of the Air Pollution Control Association. Atlantic City. June 27-July 2, 1971.)

Berg, Bengt R. Development of a New Horizontal-Flow Plate-Type Precipitator for Blast Furnace Gas Cleaning. Iron and Steel Engineer. October 1959. p 93-100.

IRON AND STEEL INDUSTRY (Cont)

Weise, William H. Blast Furnace Flue Dust Treatment Facilities. Sewage Ind. Wastes. 28(11):1398-1402, November 1956.

Ferrari, Renzo. Experiences in Developing an Effective Pollution Control System for Submerged Arc Ferroalloy Furnace Operation. Journal of Metals. April 1968. p 95-104.

Yocum, J. E. and Chapman, S. The Collection of Silica Fume with an Electrostatic Precipitator. Journal of Air Pollution Control Association. 8(1):45-52, May 1958.

Kolbe, F. Dry Lurgi-Type Electrical Dust Precipitation of the LD Process. Trans. Berg-und Huttenmannische Monatshefte. 104(2):26-31, 1959.

Rasworschegg, H. Waste Heat Boiler Systems and Gas Cleaning Plants Downstream of LD Vessels and Converters. Trans. Berg-und Huttenmannische Monatschefte. 104(2):31-40, 1959.

Granville, R. A. The Capital Costs of Some Waste-Gas Cleaning Plants for Use in Iron and Steel Works. Iron and Steel Inst. Special Report No. 61. 1958. p 23-30.

Speight, G. F. Best Practicable Means in the Iron and Steel Industry. Chem. Engr. (London). 9(217):132-139, March 1973.

COPPER INDUSTRY

Restriction of Emission Copper-Ore Mills. Verein Deutscher Ingenieur 2101, September 1966.

Smiezak, A., Dalewski, A., and Peszat, S. Investigation of a Dust Control System for Gases from Shaft Furnaces for the Production of Copper Matte. Proceedings of the Metallurgical Institutes. (1-2):21-30, 1972.

ALUMINUM INDUSTRY

Konopka, A. Particulate Control Technology in Primary Nonferrous Smelting. (Presented at American Institute of Chemical Engineers and Institute Mexicano de Ingenieros Quimicos Joint Meeting, 3rd. Denver. September 1970.)

McCabe, Louis C. Atmospheric Pollution. Industrial and Engineering Chemistry. 44(5):121-122A, May 1952.

Schiele, G. Electrical Cleaning of Waste Gases from Electrode Furnaces. Aluminum. 43(3):171-174, March 1967.

ALUMINUM INDUSTRY (Cont)

Bakke, Even. The Application of Wet Electrostatic Precipitators for Control of Fine Particulate Matter. (Presented at EPA's Joint U.S.-U.S.S.R. Symposium on Control of Fine Particulate Emissions from Industrial Sources. San Francisco. January 15-18, 1974.)

Rossano, August T. Jr. and Pilat, Michael J. Recent Developments in the Control of Air Pollution from Primary Aluminum Smelters in the United States. (Paper EN-16F. Clean Air Congress, 2nd. Washington. December 6-11, 1970.)

Report by Singmaster and Breyer. Emission Control Techniques: Removal Equipment - Electrostatic Precipitators. Air Pollution Control in the Primary Aluminum Industry. 1, Sec. 5. July 1973. p 29-33.

PULP AND PAPER INDUSTRY

Electrostatic Precipitation: New Designs Spell Wider Use. Chem. Eng. 77:32-33, July 1970.

GENERAL

Electrostatic Precipitator,. Fiber-Dyne Manufacturer's Literature.

Charged Droplet Scrubber. Manufacturer's Literature (Civiltech).

Ochi, Noritaka. Various Dust Collectors and Their Useful Applications. Japan Society of Mechanical Engineers, Tokyo. (Presented at Seminar on Recent Technology on Public Pollution Control, 370th. Fukuoka. December 11-12, 1972.)

Wase, Kjell. Luftfororeningar fran Kupolugnar Och Tekniska Mojligheter Att Begransa Dessa. Information Fran Statens Naturvardsverk, Volume I, 1968 (National Swedish Nature Conservancy Office.)

Domanski, Ireneusz. Design and Operation of Wet Electrostatic Dust Precipitators. Cospodarka Paliwami J. Energia. (1):1-16, 25-27.

Okamoto, Yasuo. Recent Dust Collectors and the Electrostatic Precipitator. (Presented at Seminar on Plastics Used in Public Nuisance Prevention Devices and Their Processing Techniques. Osaka. February 19-20, 1973.)

Adachi, N., Kimura, M., and Hashimoto, S. Electric Filtration of SO_2. Taiki Osen Kenkyu (J. Japan Soc. Air Pollution). 2(1):98-100, 1967.

GENERAL (Cont)

Adachi, T. Study on the Removal of SO_2 Gases by a Wet-Type Electric Precipitator. Taiki Osen Kenkyu (J. Japan Soc. Air Pollution). 4(2):188-193, November 1970.

Inyushkin, N. and Averbukh, Ya. Influence of Gas Flow Pressure Conditions on Dust Collection in an Electrostatic Field. Soviet J. Non-Ferrous Metals. 35:35-38, 1962.

Restricting Dust Emission in Blast-Furnace Operation. VDI Kommission Reinhaltung Der Luft. (Duesseldorf). February 1959.

Robinson, M. Electrostatic Precipitation. Air Pollution Control. Werner Strauss, Part 1, 275. John Wiley & Sons, New York, 1971.

Yurev, N. Purification of Industrial Gases Containing a Large Amount of Arsenic. Tsvetnye Metally. 45(2):26-30, 1972.

Hydro-Precipitrol, Fluid-Ionics Systems. Manufacturer's Literature.

Funke, G. Dust and Dust Collection Problems of Cement Shaft Kilns. Zement-Kalk-Gipa. 13:137-144, April 1960.

Johnson, G. A. and Peterson, K. F. Air Pollution Prevention at a Modern Zinc Smelter. Air Repair. 3(3):173-178, February 1964.

Ertl, D. W. Electrostatic Gas Cleaning. South African Mech. Engr. 16(8):159-168, March 1967.

Bauer, Hans-Dieter and Bruckmann, Erich. Efficiency of Precipitators - A Critical Examination Under Special Consideration of the Particle Size Distribution and The Concentration of the Dust. Staub. 33(3):126-129, March 1973.

Matsuyma, T. (illegible), Aoki, K., and Koya, N. A Chemical Engineering Study of the A107 Electric Dust Collector. (Report No. 2. 5th Fall Meeting of the Society of Chemical Engineers, 1971.

Weber, E. Applicability of Test Stand Results in Practice for Precipitators. Staub. 33(3):129-133, March 1973.

Batel, Wilhelm. The Electrostatic Precipitator: Development State and Trends. Staub. 33(3):133-140, March 1973.

Underwood, G. Removal of Sub-Micron Particles from Industrial Gases, Particularly in the Steel and Electricity Industries. International Journal of Air and Water Pollution. 6:229-263, 1962.

GENERAL (Cont)

Stairmand, C. J. The Design and Performance of Modern Gas-Cleaning Equipment. Institute of Fuel. 20, February 1956.

Pottinger, J. F. The Collection of Difficult Materials by Electrostatic Precipitation. Australian Chem. Process. Eng. 20(2):11-23, February 1967.

Engels, G. Cupola Furnace Dust Removal. 127:132-167. Giesserei Verlag, 1967.

Strindehag, O. M. Liquid Surface Electrostatic Precipitator. Review Scientific Instruments. 38:95-99, January 1967.

Gilbert, Nathan. Removal of Particulate Matter from Gaseous Wastes - Wet Collectors. Department of Chemical Engineering. University of Cincinnati. 1961. p 39-40.

Soo, S. L. Electro-aerodynamic Precipitator. U. S. Patent No. 3,500,614. March 1970.

Parkington, J.W. and Laurie-Walker, S. Attainment of High Precipitation Efficiencies on Fine and Sub-Micron Dusts and Fumes. Colloques Internationaux du Centre National de la Recherche Scientifique. (Paris). (102):321-362, 1961.

Guthmann, K. Air Cleaning in Foundries, Especially Steel, III, Dedusting of Fumes from Electric Arc Furnaces. Radex Rundschau (7):323-347, 1958.

Beaver, C. E. Cottrell Electrical Precipitation Equipment - Some Technical and Engineering Features, Recent Development, and Applications in the Chemical Field. Trans. Amer. Inst. Chem. Eng. 42:251-261, 1946.

Electric Chimney Attracts Smoke and Washes it Away. The Engineer. 33, Decmember 1970.

Stairmand, C. J. Selection of Gas Cleaning Equipment: A Study of Basic Concepts. Filtration and Separation. 1:53-63, January-February 1970.

Heinrich, R. F. and Anderson, J. R. Electro-Precipitators in the Chemical Industry - Their Applications, Cost and Operation. Brit. Chem. Eng. 2:75, February 1957.

Knott, D. R. J. The Heenan Aeropur Electrofilter. Public Cleansing (London). 60(6):274-276, June 1970.

Electro-Aerodynamic Precipitator. Steam Heating Engineer. 40(469):18-19, December 1970.

GENERAL (Cont)

Rathgeber, Ferdinand. Electric Filters for Dry and Wet Separation. Wasser Luft Betrieb. 14(1):456-460, November 1970.

Yurev, N. V. Purification of Industrial Gases Containing a Large Amount of Arsenic. Tsvetnye Metally. 45(2):26-30, 1972.

Device for Precipitation and Collection of Charged Particles from a Gas. (To Aktiebolaget Atomergi) British Patent 1,176,425, Nuclear Science Abstracts. 24(8), 1970.

Eisner, J. H. Possible Uses of Modern Electric Gas Cleaning Plants. Wasser, Luft, and Betrib. 14(10):394-402, October 197 (digit missing).

Wet Precipitator Introduces New Concept. Paper Trade Journal. July 1973.

Sargent, Gordan D. Gas/Solid Separations. Chemical Engineering. February 1971.

Soo, S. L. and Rodgers, L. E. An Electro-Aerodynamic Precipitator. (Paper No. G8-104 61st Annual Meeting, Air Pollution Control Association. St. Paul. June 26, 1968.)

Soo, S. L. and Rodgers, L. W. Further Studies on the Electro-Aerodynamic Precipitator. Powder Technology. 5(1), November 1971.

Wright, F. Dynamic Dust and Fume Precipitators. Iron and Steel Inst. Special Report 61. 1958. p 103-108.

Bothe, R. Increasing the Efficiency of Existing Dust Removal Plants for Flue Gas. Stahl und Eisen. 89:30-35, January 1969.

Guthmann, Kurt. Operation and Maintenance of Electrical Dust Collectors. Staub. 26(4):13-15, April 1966.

Weber, E. Dust Extraction from Cupolas with Special Reference to the Costs Involved. Geisserei. 49(6):136-142, 1962.

Koglin, Waldemar. The Load Dependence of Electrostatic Precipitators. Staub. 28(4):10-15, October 1968.

Koglin, Waldemar. Separation of Dusts and Mists in Wet Electrostatic Precipitators. Staub. 30(4):6-8, April 1970.

Eyraud, C., Joubert, J., Morel, R., Henry, C., and Roumesy, B. Investigations of a New Dust Collector with Electrostatic Water-Spraying. International Convention on Air Pollution. Paper V/5. (London) 1966.

GENERAL (Cont)

Review of the Exhibition 'Reinhalting Der Luft'. Staub. 30(2): 53-54, February 1970.